UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE BIOLOGIA ANIMAL

Climate Change implications on landscape functional connectivity: a case study with insects in Terceira Island, Azores

Bruno Miguel Almeida Aparício

Mestrado em Ecologia e Gestão Ambiental

Dissertação orientada por:
Doutora Maria João Cruz
Doutor Fernando Ascensão

2016

'Preservation should imply perpetuating the dynamic process of presettlement landscape'
Reed F. Noss (1983)

Acknowledgement

First of all, I would like to thank to my supervisors Maria João Cruz and Fernando Ascensão, for their unflagging support, guidance and optimism throughout the last year of work. I know that sometimes I might be annoying, but you were always there to answer to my (many!!) questions. Also, Professor Paulo Borges and Professor José Cascalho that helped me in several stages of the study and followed very close the thesis construction. Realistically, without the participation of one of the above, the present thesis would not have 1/5 of its present quality, so I am thankful for that.

I would like to thank to all the CCIAM team that received me in a splendidly way and made me feel like part of the team. Special thanks are due to all the people in room 1:4:21 (Susana, Tomás, Luís, Andreia, Sílvia, Filipa, Rodrigo and Cristiana) for 'lend' me a place where I developed this thesis, and for receiving me in the best way possible. Thanks also to all the people in the PRAC project. A thank you note is also due to Cibio-Inbio research team based at ISA, who, like CCIAM, received me in the best way possible.

Special thanks are due to CCIAM and cE3c that financed all my travels to Azores, and gave me the opportunity to participate in an International Conference. I must also acknowledge Ângela Antunes for helping me with all the bureaucracies related with the travels.

To the Azorean biodiversity group, that received me in 'their home' during several weeks, a lot of thanks.

To Pedro Neves and David Avelar, for allowing me to use their computers, significantly reducing the time of simulations.

To all my friends, for all the support and interest in my thesis.

To my girlfriend for all the support, patience and motivation. Thank you for being always with me.

This part has to be in Portuguese:
À minha família, particularmente aos meus pais, irmão, avó Maria, tio Juka e Bisa, obrigado por todo o apoio incondicional que me deram (e dão!), não só durante os cinco anos de Faculdade, mas durante toda a minha vida. Nada disto seria possível sem vocês, por isso vos dedico esta dissertação.

Muito Obrigado

Abstract

Biodiversity is under unprecedented pressure due to multiple anthropogenic threats, including habitat loss and fragmentation. Climate change is posing an extra and critical pressure in the natural systems, forcing species to adapt or to perish. As a result, many species are shifting their ranges, accompanying the shift of optimal climate conditions. However, this range shift can be quite challenging in islands, not only due to the competing interest for land between humans and nature (e.g., habitat corridor vs. agriculture areas) but also because the optimal conditions may cease to exist within the island area in the near future. It is therefore critical to promote the creation and conservation of key corridor areas linking high quality habitat, in order to facilitate the dispersion of organisms when required while maintaining the metapopulation integrity. Nonetheless, the creation of such corridors can be complex and resource consuming. Moreover, there is often an enormous lack of knowledge regarding species' movement preferences, which further increases the uncertainty about where to maintain/restore the functional connectivity to enhance species dispersal capacity. Here, we developed a framework to quantify and face such uncertainty using agent-based modeling (ABM), and applied it in the Terceira island, Azores, using five endemic ground-dwelling insect species as case studies. Our model framework first feeds on expert knowledge regarding land cover resistance to movement, and is then tested and compared against known occupancy patterns. We compare the results from our agent-based model with three well-known modeling techniques (Circuit-theory, Least-Cost Path and Dispersal Paths). Using this approach, we were able to quantify the amount of projected suitable area per species that are more used, identifying crucial areas for species' movement, to evaluate the dispersal opportunities given the current land-uses. Moreover, we apply the ABM here developed to test recent reforested sites in Terceira island, regarding the potential that these sites have to enhance functional connectivity between native sites. Our results have shown that (i) species are not able to equally use all the projected suitable areas, and future climate conditions further reduces the amount of quality areas for movement, i.e. species may be more vulnerable than once anticipated. (ii) The most well-connected native sites are located near Biscoito da Ferraria, and we classified these sites as priority to restoration. Serra de St. Bárbara is fairly disconnected and restorations that connect this site to Matela and Biscoito da Ferraria should also be considered. Finally, recently restored sites appear to not be sufficient to ensure an effective connectivity between native sites, as they were proven to perform equally and some times worse than randomly generated reforestations. This thesis should be taken into account when designing new reserves or corridors in Terceira Island.

Key-words: Agent-based model; Ecological restoration; Corridor design; Island connectivity; Functional Connectivity

Resumo

A biodiversidade está sobre uma pressão sem precedentes devido às crescentes ameaças de origem antropogénicas, onde se realça a destruição e fragmentação de habitat. As alterações climáticas posicionam-se como um factor extra e critico à sobrevivência das espécies. Como consequência, várias espécies estão no caminho da extinção, sendo que recentemente muitas delas já se tornaram extintas. De facto, as soluções implementadas para salvaguardar a biodiversidade terrestre continuam a não corresponder às expectativas, levando ao uso do termo 6ª extinção em massa.

Uma das respostas verificadas das espécies às alterações climáticas é a alteração da sua distribuição no espaço. Contudo, tal mudança na distribuição requer a migração das espécies, muitas vezes através de habitats não-nativos e inóspitos. Como a adaptação via microevolução (mudança no genoma da população) não é passível de ocorrer em tão pouco tempo disponível, existe o consenso cientifico de que a melhor acção é garantir que a migração das espécies para os locais mais adequados à sua sobrevivência. Para tal, a construção de corredores ecológicos é sugerida como a medida mais promissora para adaptar a paisagem às alterações climáticas. A sua construção foi já comprovada empiricamentepor ser responsável pelo aumento da taxa de migração e do movimento das espécies entre parcelas de habitat. Estudos teóricos (com recurso a modelos computacionais) mostraram que os corredores ecológicos poderão ter também a capacidade de contrabalançar a diferenciação genética entre parcelas de habitats, aumentando também a diversidade genética e o número efectivo populacional de cada parcela. Em suma, os corredores ecológicos parecem melhorar a conectividade entre dois ou mais locais, podendo ultimamente alterar a composição das comunidades. Contudo, devido à competição com outros usos do solo, geralmente com maior importância social e económica, a construção de tais corredores pode ser bastante conflituosa. Tais conflitos são maiores quando a área disponível é pequena, como no caso de ilhas pequenas. Em adição, num contexto de alterações climáticas, os locais climaticamente adequados para cada espécie podem-se tornar restritos ou mesmo deixar de existir. De modo a identificar eficazmente os locais mais importantes para as espécies, nos últimos anos um grande número de modelos computacionais têm sido desenvolvidos e aplicados à ecologia.

A presente dissertação de mestrado enquadra-se na visão acima referida. Aqui, desenvolvemos um *Agent-Based Model* (ABM) em ambiente de NetLogo e aplicamos o mesmo a cinco espécies de escaravelhos endémicos dos Açores, na Ilha Terceira. As espécies utilizadas no estudo são (ordenadas da mais especialista quanto ao habitat para a mais generalista): *Trechus terrabravensis* Borges, Serrano and Amorim, 2004 (Insecta, Coleoptera, Carabidae) *Cedrorum azoricus azoricus* Borges and Serrano, 1993 (Insecta, Coleoptera, Carabidae), *Drouetius borgesi borgesi* Machado, 2009 (Insecta, Coleoptera, Curculionidae) *Aphrodes hamiltoni* Quartau and Borges, 2003 (Insecta, Hemiptera, Cicadellidae) e *Alestrus dolosus* (Crotch, 1867) (Insecta, Coleoptera, Elateridae).. O facto de os ABMs requererem a construção de um código informático na sua linguagem própria, permite ao modelador ter controlo total sobre o seu modelo, permitindo da mesma forma o estudo de características e padrões que de outra forma não seria possível. Aqui comparamos também o ABM desenvolvido com três outros tipos de modelação: *Circuit theory*, *Least-cost Path* e *Dispersal Paths*. Todos os modelos foram inicializados com os mesmos dados (i.e. uso do solo, declive e valores de resistência ao movimento de cada espécie, referente a cada um dos anteriores proveniente de *expert knowledge*). A comparação é realizada através da aplicação de um *genelarized linear model* (GLM) binomial, que avalia a adequação de cada mapa de conectividade gerado pelos diferentes

tipos de simulação usados, tendo em conta padrões observados de presença/ausência das espécies em 182 *pitfalls* espalhadas em toda a ilha. Após verificarmos que, tal como antecipado, o nosso ABM explica sempre mais variabilidade (i.e. apresenta um valor de R^2 superior) do que os restantes métodos, este foi aplicado a outras questões emergentes:(i) investigar de que forma se relaciona a área projectada como óptima para cada espécie para condições climáticas presentes e do fim do século (i.e. *Species Distribution Model* – SDM) com as áreas mais utilizadas pelas espécies durante os seus movimentos (i.e. o mapa de conectividade gerado anteriormente). Com esta questão pretendemos avaliar se cada espécie é capaz de utilizar igualmente a área onde a sua distribuição potencial é projectada por modelos climáticos; (ii) investigar quais os corredores que existem actualmente que permitem a troca de indivíduos entre zonas de vegetação nativa diferentes. No seguimento destes resultados, foi-nos possível classificar os locais de vegetação não nativa quanto à prioridade de reflorestar tais locais, em função da conectividade; (iii) Por fim, avaliar a contribuição para a conectividade funcional entre duas importantes parcelas de habitat (Serra de Santa Bárbara e Biscoito da Ferraria) que 10 hectares (divididos em quatro áreas) recentemente reflorestados oferecem, comparando a sua *performance* com: a mesma área na ausência destas mesmas recentes reflorestações; e com reflorestações geradas aleatoriamente entre as duas parcelas de habitat (mantendo a proporção).

Os resultados do nosso modelo indicam que, em relação à área mais utilizada, esta é sempre menor do que a área projectada como óptima para a espécie, com reduções até 7600 hectares (para a espécie *Alestrus dolosus*, representando 62% da sua área projectada). Em adição, não só existe a diminuição da área mais utilizada face à área climática adequada projectada (SDM) para o presente, como se verifica também uma diminuição entre a quantidade de área mais utilizada no presente e no futuro (fim do século), indicando assim que a perda de locais óptimos para a espécie devido às alterações climáticas, afectará locais que outrora seriam adequados para a espécie habitar. O caso mais gravoso encontrado entre as espécies estudadas pertence ao *Trechus terrabravensis*, onde a quantidade de área climática adequada projectada para o fim do século é de apenas 175 hectares, sendo que a área mais utilizada nos seus movimentos corresponde a apenas 10 hectares (6% da área projectada).

Relativamente aos corredores identificados, o modelo reconheceu um maior número de migrantes na zona perto da Biscoito da Ferraria (zona central da ilha). Este resultado é encarado sem grande surpresa, uma vez que se trata do local onde o número de parcelas de habitats é maior, sendo naturalmente menor a distância entre parcelas, facilitando desta forma os movimentos entre os mesmos. Da mesma forma, a zona da Serra de Santa Bárbara não exibe muito movimento entre parcelas de habitat, isto porque não existe a proximidade entre fragmentos que se verifica perto da Biscoito da Ferraria. Este resultado pode significar que, embora possuindo grandes dimensões, o local da Serra de Santa Bárbara poderá estar relativamente isolado face a outros fragmentos de vegetação nativa. Por consequente, devido ao elevado número de indivíduos que conectaram as parcelas de habitat perto da Biscoito da Ferraria, estes locais foram identificados como prioritários para restauração para o total de espécies estudadas sob as condições climáticas actuais, e para quatro das cinco espécies para as condições futuras. Outros locais de importância especial encontram-se localizados perto da zona da Matela, sendo que reflorestações nestes locais iria permitir conectar a Serra de Santa Bárbara, Matela e a Biscoito da Ferraria. A priorização dada a estes locais não sofreu alterações entre as condições climáticas presentes e futuras, sendo prioritária para três das cinco espécies (sendo que as excepções são *Cedrorum azoricus azoricus* e *Trechus terrabravensis*, as espécies mais restritas da amostra). *Cedrorum azoricus azoricus* e *Trechus terrabravensis* apresentaram o menor número de migrantes sob as projecções climáticas futuras, reflectindo a sua vulnerabilidade e necessidade de acções localizadas.

Relativamente às reflorestações que recentemente tomaram lugar, verificou-se que existe sempre um aumento da conectividade funcional, independentemente da espécie considerada, sempre que as reflorestações recentes são consideradas, em detrimento da ausência de reflorestação. Contudo, estas reflorestações mostraram uma *performance* que não difere estatisticamente de quando a reflorestação é feita de modo aleatório.

O presente estudo indica que, por um lado, o uso do solo não deve ser negligenciado aquando da projecção da área óptima para uma determinada espécie, tendo-se reflectido no nosso estudo sobre a forma da diminuição da área mais utilizada nos movimentos das espécies, comparando com a projecção do SDM. Por outro lado, mostrámos que um ABM é capaz de superar outras formas de modelação da conectividade, permitindo ainda estudos mais variados. Quanto às medidas de gestão, identificámos que os locais onde o restauro é prioritário encontra-se perto da zona da Biscoito da Ferraria, quer para as condições climáticas presente e futuras. Outro local que deverá ser considerado encontra-se perto da zona da Matela, sendo que intervenções nesta zona iriam potenciar a conectividade funcional entre duas das mais importantes parcelas de habitat dos Açores (i.e. Serra de St. Bárbara e Biscoito da Ferraria). Podemos ainda constatar que as recentes intervenções de restauro contribuem para uma maior conectividade funcional das espécies estudadas, podendo embora o seu design não estar optimizado. Desta forma, futuras intervenções na paisagem com fins de conservação deverão ter em conta os resultados aqui apresentados, e vários cenários de intervenção deverão ser hipotetizados e testados (envolvendo a população local), de modo a maximizar o incremento na conectividade funcional em função do investimento.

Palavras-chave: Agent-based model; Restauro ecológico; Corredores ecológicos; Conectividade de ilhas; Conectividade funcional

Contents

List of Figures

List of Tables

List of abbreviations

ABM – Agent-Based Model

CO_2 – Carbon Dioxide

GCM – General Circulation Model

GDP – Gross Domestic Product

GHG – Green-House Gases

GLM – Generalized Linear Model

GPS – Global Positioning System

IPCC – International Panel on Climate Change

LCP - Least-Cost Path

PRAC - Regional Plan for Climate Change of Azores

RCM – Regional Climate Model

RCP – Representative Concentration Pathway

SDM – Species Distribution Model

Chapter 1 – General introduction

1.1 Problem overview: Climate change – evidences for a warmer environment

Earth climate is the result of the interaction of a variety of complex processes that occur at atmospheric level, oceanic level, terrestrial surface and cryosphere level (Trenberth & Hurrell, 1994; IPCC, 2007). By resulting from such complex interaction, climate is rather cyclic than static, and is known to have changed greatly in the past, both between and within glacial and interglacial eras (Dansgaard *et al*., 1993). For example, during the last glacial era, it was estimated that temperature at the surface was 5°C to 7°C lower than the current temperature, and sea level was about 100 to 120 meters lower than current levels (Santos & Miranda, 2006), whereas in the last interglacial era the temperature was estimated to be 5°C warmer than today's (Andersen *et al*., 2004). Recently, the Intergovernmental Panel on Climate Change (IPCC) recognized that it '*is certain that Global Mean Surface Temperature has increased since the late 19th century (…) and the first decade of the 21st century has been the warmest*' (IPCC, 2013). In fact, not only the global temperature is rising (0.85°C warmer on average than in 1880 – see Figure 1.1a), but also the precipitation, humidity and extreme events frequency are already changing or are likely to change (IPCC, 2013). The current climate warming projection far exceeds the variability of the past 1000 years, and is greater than the estimated global temperature change for the previous interglacial era (Crowley, 2000). Most importantly, the rate in which is occurring is unprecedented.

Human activities, mostly the continuous emission of green-house gases (GHG), are very likely to be the main cause of the current climatic changes (IPCC, 2013). Such GHG are the result of deforestation, and fossil fuel combustion, and are responsible for an increase in the concentration of carbon dioxide (CO_2) of over 30% when compared with pre-industrial values (from 280 ppm for pre-industrial age to 374 ppm in 2004) (Santos & Miranda, 2006), leading to an increase in radiative forcing and, consequently, in green-house effect (see Figure 1.1b). Furthermore, even if humanity restrains its emissions within the next few decades, consequences like temperature and sea level rise, spreading of pests and tropical diseases, ocean acidification and biodiversity loss are more likely to happen than not to happen (IPCC, 2007). All these changes in the natural systems will ultimately affect human health and social and economic systems (see detailed description in McMichael *et al*., 2006).

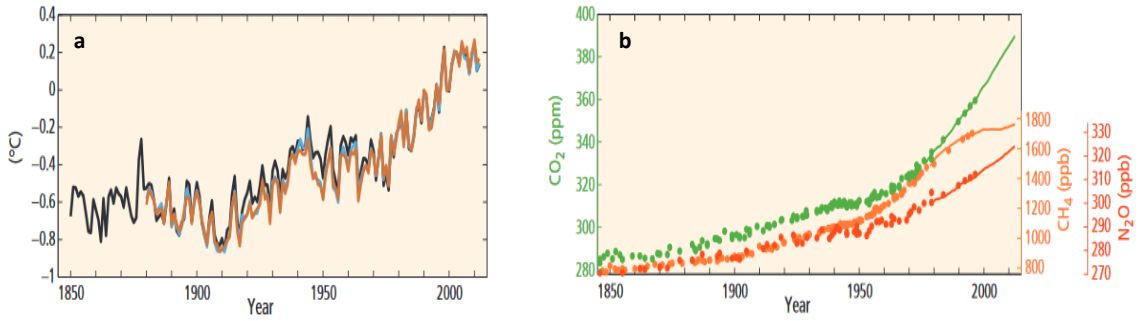

Figure 1.1 - Observations of changing climate: a) Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005. Colors indicate different data sets. b) Atmospheric concentrations of greenhouse gases. Carbon dioxide (CO_2) presented with green, methane (CH_4) presented with orange and nitrous oxide (N_2O) presented with red. Dots represent data from ice core while lines represent direct atmospheric measurements. Adapted from IPCC (2014).

1.1.1 Climate change scenarios – Understanding the basics

General Circulation Models (GCMs), a 3D representation of Earth's atmosphere, have been widely used to represent and quantify climate change (e.g. Cox *et al*., 2000). GCMs are complex models that reproduce the processes that affect weather, and thus they can be used to study (model) the effects of changing GHG concentrations, and thus produce climate change scenarios. However, such models produce climate matrixes with very low resolution (in the order of hundreds of kilometers) that can compromise climate change impact studies in the required detail. This is particularly true for regions of complex topography, coastal or island locations, and in regions of highly heterogeneous land-cover (Wilby *et al*., 2004). In order to overcome this handicap, it is normal to resort to Regional Climate Models (RCMs). These models are projected using downscaling techniques, that consist on developing climate scenarios for a point or small area using the projections of a climate model (normally a GCM) but correcting them with regional climate information, originated from local observations (Wilby *et al*., 2004). A RCM varies the atmospheric properties modeled by a GCM, and is 'nested' within its grid. The overall projected map has grids around tens of kilometers, or less (Lopes, 2008).

Long-term climate change projections require various assumptions on human activities and natural effects that have the ability to modify the climate over the decades and centuries to come (IPCC, 2014). A Climate scenario is a projection of the climate system response to emission or concentration scenarios regarding GHG (among others). The most recent climate scenarios from the IPCC, Representative Concentration Pathways (RCPs), are defined by the total radiative forcing pathway. Radiative forcing should be interpreted as the cumulative measure of human emissions of GHG derived from all sources and expressed in Watts per square meters (IPCC, 2014). These new scenarios specify concentrations and the corresponding emissions, without being directly based on socio-economic scenarios. IPCC considered four different pathways: RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5. These scenarios description is summed up in Table 1.1 and Figure 1.2.

Table 1.1 - Summary of the four RCP scenarios based on descriptions presented in IPCC (2014) and van Vuuren *et al.* (2011).

Scenario	Brief description	CO_2 by 2100	Radiative Forcing by 2100
RCP 2.6	Mitigation scenario, which leads to a very low radiative forcing. Peak before the end of the century.	≈400 ppm (peak at 490 ppm)	2.6 W m^{-2}
RCP 4.5	Medium stabilization scenario around the end of the century.	≈500 ppm (peak at 650 ppm)	4.5 W m^{-2}
RCP 6	Medium stabilization scenario around the end of the century.	≈620 ppm (peak at 850 ppm)	6 W m^{-2}
RCP 8.5	Very high baseline emission scenario. Continues to rise after 2100.	≈950 ppm (peak at 1370 ppm)	8.5 W m^{-2}

Naturally, the increase in radiative forcing leads to the inevitable global surface warming, with different magnitudes relative to each pathway taken. Under the least severe scenario (RCP 2.6) the global average temperature is expected to rise between 0.3°C to 1.7°C and between 2.6°C to 4.8°C under the most severe scenario (RCP8.5), relative to 1986-2005 period (IPCC, 2014) (Figure 1.2). The rates of change in any of these scenarios are significantly higher than historical non-anthropogenic climate change.

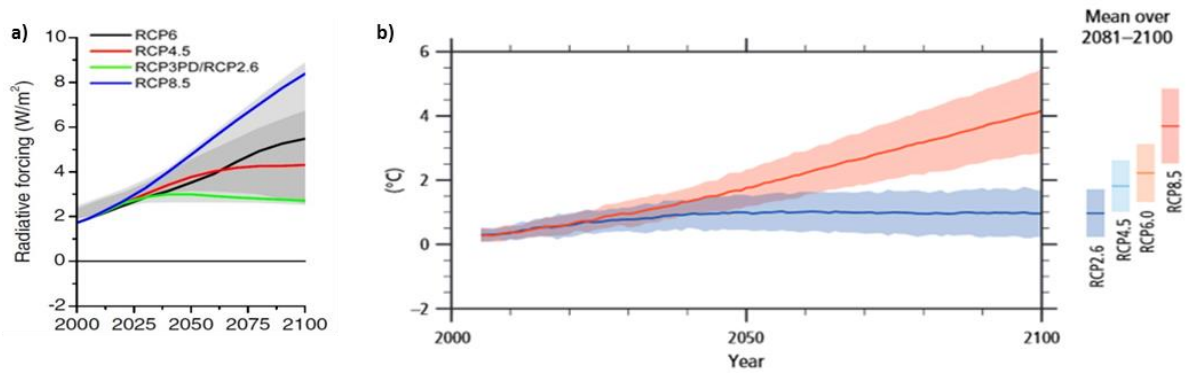

Figure 1.2 - Projections of a changing climate: a) Representation of the trends in radiative forcing. Light grey area indicates the 98th percentile and dark grey represents the 90th percentile. Adapted from van Vuuren *et al.* (2011); b) global average surface temperature change relative to 1986-2005 period, for the four scenarios. Uncertainty is represented by the shadows. Adapted from IPCC (2014).

1.2 Climate change consequences to natural systems

1.2.1 What are the Impacts?

Since the beginning of life, living beings had to constantly adapt to the natural climatic fluctuations in order to ensure long-term persistence. However, such adaptation must at least equalize the rates at which climatic change occurs, which is far from guaranteed (Bradshaw, 1991). *Taxa* that fail to adapt fast enough to tolerate the climatic changes will cease to exist (Davis & Shaw, 2001). For example, the Quaternary period has suffered numerous and intense climatic fluctuations. Such dramatic changes threatened global biodiversity and high rate of extinctions among terrestrial animals were found (Coope & Wilkins, 1994). Since environmental changes occurred rapidly, adaptation by genetic changes is unlikely to occur. Hence, assuming that species have the mobility and the space required, a range shift of their distribution that followed the changing climate is a much more likely response, with species assuming a mobile trait rather than a stationary one (Coope & Wilkins, 1994; Parmesan, 2006).

Besides migration, there are two other mechanisms that can provide adaptation from species: genetic variation (microevolution), which can be the basis of several adaptive strategies that have been observed; and adapting the phenology during short periods of time (Füssel & Jol, 2012). Because these are not the focus of the present thesis I do not provide a full description or enumeration of such changes. For this reason, Table 1.2 seeks to be an illustrative rather than an exhaustive compilation of adaptive strategies.

In this day and age, there is a consolidated awareness in the scientific community that biodiversity is under an unprecedented threat, as undergoing conservation efforts do not seem to produce the expected effect and species continue to go extinct (EEA, 2009; Barnosky *et al*., 2011). In fact, anthropogenic climate change is already affecting all natural systems, from shifts in distributions of marine species (e.g. Perry *et al*., 2005), to shifts in distribution in latitude and altitude of terrestrial species (Chen *et al*., 2011). Terrestrial species in the UK were found to be moving, on average, at a pace of 11 meters per decade in elevation and 16.9 km per decade away from the equator (Chen *et al*., 2011; Figure 1.3). However, unlike the previous migrations, current migration following climate suitability can be fairly challenging for species. This because, not only current climatic changes are occurring at an unprecedented rate (as cited above), but also because landscapes possess now a strong anthropogenic influence, which have led to habitat fragmentation. Thus, distribution shift may simply not occur and adaptation by genetic variation may require more time to occur than there is available (Davis & Shaw, 2001). Furthermore, the isolation of populations due to land-use changes can disrupt gene flow, which could lead to genetic drift and inbreeding, and eventually reductions in effective population size and in genetic diversity, reducing the genetic variability and further limiting species' adaptive capacity (Lande, 1993).

Table 1.2 - Summary of the observed and expected biodiversity responses (green rows) and consequences (blue rows) to climate change.

Biodiversity and ecosystem observed and expected responses and consequences to Climate Change	***Reference***
Shifts in species distributions along elevational and latitudinal gradients	Parmesan & Yohe (2003); Chen *et al*. (2011)
Phenological (e.g. migration, flowering or reproductive patterns) and morphological changes (e.g. body size)	Root *et al*. (2003); Sheridan & Bickford (2011)
Genetic changes in natural populations (e.g. microevolution)	E.g. Rodriguez-Trelles & Rodriguez (1998); Nussey *et al*. (2005)
Reductions in populations size and communities composition	E.g. Lemoine *et al*. (2007); Gregory *et al*. (2009)
Extinction or extirpation of isolated or range-restricted species and populations	Malcolm *et al*. (2006)
Increased spread of wildlife diseases, parasites, and zoonoses	Harvell *et al*. (2002)
Habitat loss due to sea-level rise	Wetzel *et al*. (2013)
Increased fire frequency	Westerling *et al*. (2006); Pereira *et al*. (2013)
Increased spread of invasive or non-native species, including plants, animals, and pathogens	Walther *et al*. (2002); Sax & Gaines (2008)
Disruption of Coevolved interactions (e.g. plant-pollinator interaction, reproduction-food availability or predator-prey interaction)	E.g. Visser *et al*. (1998); Visser *et al*. (2006)
Loss of genetic diversity	E.g. Rubidge *et al*. (2012)

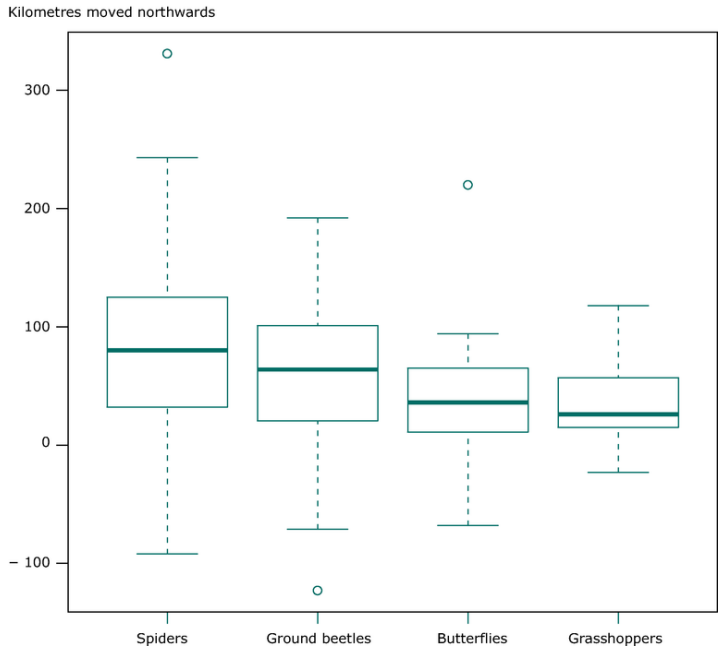

Figure 1.3 - Observed latitudinal shifts of species from four exemplar taxonomic groups, studied over 25 years in Britain: spiders (85 species), ground beetles (59 species), butterflies (29 species), and grasshoppers and allies (22 species). Positive latitudinal shifts indicate movement toward the north (poleward) while negative values indicate shifts toward the south (Equator). Open Circles are outliers. Source: Füssel & Jol (2012); data from Chen *et al*. (2011).

Habitat fragmentation and climate change are considered the two most stressful factors for species, and their interaction can have drastic effects on biodiversity (Sala *et al*., 2000). Specialist species with low capacity of migration and narrow habitats and climate tolerances, such as endemic species, appear to be the most vulnerable to climate change (Thomas *et al*., 2004; Malcolm *et al*., 2006). Furthermore, biodiversity hotspots have suffered habitat loss for a long time (Myers *et al*., 2000), and the associated reductions in populations size and opportunities to disperse may further reduce the migration rates and the survival of the species (Niebuhr *et al*., 2015), further reducing the adaptive capacity of species to climate change.

If we consider a site with limited area available to where species can migrate, with a high historical deforestation process, and high levels of endemic species dependent on endemic vegetation, the threats to biodiversity are even higher. This is the case of small islands that are home to a large set of unique species (Kier *et al*., 2009). In such sites, species migration to more suitable places is more prone to be disrupted, since these suitable sites may be unreachable or simply because they cease to exist (Courchamp *et al*., 2014). Such upcoming biodiversity loss could have extreme impacts on human systems, apart from the natural patrimony loss. For example, Naeem *et al*., (1994) found that not only the loss of biodiversity might reduce the terrestrial ecosystems capacity to capture CO_2 with anthropogenic origins, but also that ecosystems that suffered losses in biodiversity may alter or impair the services that they provide.

1.2.2 What can we do?

Current investments in management actions (e.g. protected areas) have been reported in many cases as ineffective to counteract species' extinction processes (Rodrigues *et al*., 2004). this may be due to poor supervision or management practices (e.g. Françoso *et al*., 2015), or inadequate design due to lack of knowledge on species distribution and connectivity (Williams *et al*., 2005) or conflicts with economic interests (e.g. Jenkins *et al*., 2015). Moreover, climate change will further reduce the effectiveness of protected areas: due to their static characteristics, 58 ± 2.6% of European terrestrial plants and vertebrate species are estimated to lose suitability inside the national protected areas, by 2080, considering climate change. Considering the current sites of Natura 2000 network, the loss of suitable niches would be even higher, of 63 ± 2.1%. In fact, current Natura 2000 sites are projected to retain climate suitability for species no better and sometimes less effectively than unprotected areas by 2080 (Araújo *et al*., 2011).

Although there is some debate around the best strategies to deal with climate change impacts to biodiversity (Hodgson *et al*., 2009; Doerr *et al*., 2011), there seems to be a high concordance between authors that the best way to reduce the negative effects of climate change on biological diversity is by increasing species' functional connectivity (Heller & Zavaleta, 2009; Krosby *et al*., 2010). Functional connectivity is perceived as the '*degree to which the landscape facilitates or impedes movement among resource patches*' (Taylor *et al*., 1993), being dependent on how animals are capable of perceive the surrounding landscape structure. Hence, functional connectivity is not only dependent on the landscape structure, but also on the species that is considered. Functional connectivity can be increased by creating ecological corridors (Heller & Zavaleta, 2009). Corridors have been found to increase the movement of multi-taxa between patches of habitat and migration rates, species richness and abundance (Andreassen *et al*., 1996; Haddad *et al*., 2003; Damschen *et al*., 2008; Gilbert-Norton *et al*., 2010). In addition, corridors have the ability to reduce the genetic differentiation between patches of habitat and increase the genetic diversity and effective population size within patches of habitat (Christie & Knowles, 2015). However it has been feared in the past that ecological corridors could also lead to biological disadvantages, such as the spread of diseases or invasive species, or miss-leading animals in their migration (see Simberloff *et al*., 1992). Haddad *et al*. (2014) presented empirical evidences showing that the proposed costs are greatly outweighed by their conservation benefits. Figure 1.4 exemplifies the assistance that such corridors can provide to species migration under climate change scenarios, allowing specialist species to reach their new optimal site.

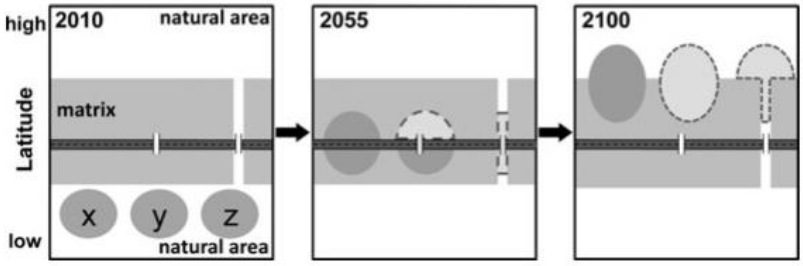

Figure 1.4 - Effect of landscape structure on the ability of species migration following climate change by 2100. Three different type of species are illustrated: a generalist species x, with a high tolerance and flexibility, that can move through different habitat matrix; a species y, that can move in a non-native matrix, but is unable to cross barriers, such as highways, in the absence of corridors; and a specialist species z, that can only cross non-native habitats when in presence of corridors. Native areas are represented in white and non-native matrixes are represented in grey. Figure from Krosby *et al*. (2010).

Once again, the competing interest between humans and nature conservation are higher when available land is limited (e.g., habitat corridor vs. agriculture areas), making the design of protected areas even more challenging, especially in islands. Furthermore, conservation outcomes appear to be less durable when conservationists impose their will in detriment of others (Redpath *et al*., 2013). However, and although recommended, stakeholder engagement is not easy to implement and often does not produce the expected outcomes (Collins *et al*., 2005). Such failure is often associated with deficiency of communication strategies and in the information provided to the stakeholders (Koschke *et al*., 2014), which can ultimately undermine conservation actions. Recently, Martinez-Harms *et al*. (2015) proposed that future studies, should evaluate the performance of proposed measures and the consequences of alternative management actions and also facilitate a closer engagement between scientists and stakeholders. Such approach would also ensure a long-term conservation benefit (Redpath *et al*., 2013). Hence, it is essential not only to use scientific studies to proper identify areas that maximize the investment (obtained by comparing different outcomes of different measures or options) but also to include local population in the discussion of such plans.

1.3 Azores characterization: land-use, biodiversity and climate

The Azorean archipelago is located in the North Atlantic (37° to 40° N latitude and 25° to 31° W longitude) and is composed by nine different Islands, with a total area of 225 thousand hectares. Islands are usually grouped in three groups: a western group (Flores, Corvo), a central group (Faial, São Jorge, Graciosa, Pico and Terceira) and an eastern group (São Miguel and Santa Maria).

The archipelago extends for around 615 km and is at a distance of 1300 km from mainland Portugal (the nearest mainland). Islands' age differ significantly among each other, being the older Santa Maria Island, with 8.12 million years, and the most recent Pico Island, with 0.27 million years (Figure 1.5). From a biogeographical view, the Azorean archipelago is grouped in the Macaronesian province, together with the archipelagos of Cape Verde, Canary Islands and Madeira). The present study focus on Terceira Island, the third biggest and oldest island of the archipelago, with approximately 402 km^2 and 3.52 million years (Figure 1.5).

1.3.1. Historical land-use changes and current land-use

Azorean original natural vegetation is Laurisilva forest, a humid evergreen broadleaf forest. Azorean Laurisilva differs from Madeira and Canary Islands as it is composed by only one species of Lauraceae: *Laurus azorica*. It also includes luxuriant bryophyte communities and several species of sclerophyllous, and microphyllous trees and shrubs (Gabriel & Bates, 2005). The native vegetation areas are characterized by a dense shrub and tree cover, closed canopy and high presence of bryophytes. The tree cover is generally of small size (usually up to 5 meters), as consequence of the narrow soil and rugged terrain where they occur (Borges *et al*., 2006). Such sites are also characterized by high levels of humidity and low light at ground level.

Generally, the human settlement on islands is followed by the destruction of native vegetation (Cardoso *et al*., 2009; Kier *et al*., 2009; Connor *et al*., 2012). The Azorean archipelago is no exception, with the native vegetation being reduced progressively since around AD 1440. During the XIX century, the Azorean archipelago suffered a great enthusiasm with gardening, and a lot of exotic plants were introduced (Martins, 1993). Later, many of those became invasive (being the most threatening the Japanese hydrangeas *Hydrangea macrophylla*, *Hedychium gardneranum* and the Australian *Pittosporum undulatum*). In fact, all of the species listed above are part of the top 100 for the most threatening invasive species in Macaronesian islands (Silva *et al*., 2008). After the Second World War, the destruction of native areas increased significantly after the reforestation of some locals of the archipelago with *Cryptomeria japonica*, known for its fast grow and large dimensions. In addition, around the same time, a great amount of terrain was converted into pastures, as the government reinforced the development of cattle and milk production (Martins, 1993). As a consequence, nowadays native vegetation occurs in less than 3% of its original distribution, being restricted to few high altitudinal areas: Terceira Island have the highest amount of native vegetation area, of around 14%, and Graciosa and Corvo Islands do not preserve any native area (DROTRH, 2008; Gaspar *et al*., 2008; Figure 1.5). Even though, these sites are thought bear most of the Azorean terrestrial endemic plant and animal species (Triantis *et al*., 2010).

Currently, invasive plants threat the remaining native vegetation areas. Species like *Pittosporum undulatum* and *Hedychium gardneranum* are particularly worrisome due to their ability to colonize and replace native areas. The replacement of such native areas with non-native plant species would have severe impacts on the archipelago biodiversity, since endemic and native arthropods species' richness was found to be higher in these areas (Cardoso *et al*., 2009). Furthermore, native vegetation areas present the lowest number of introduced arthropod species, while highly managed areas (i.e. intensive pastures) presented the highest number of introduced arthropod species and the lowest number of native and endemic species (Meijer *et al*., 2011; Florencio *et al*., 2016). Hence, native vegetation areas seem to be acting as a buffer zone to the dispersion of exotic fauna.

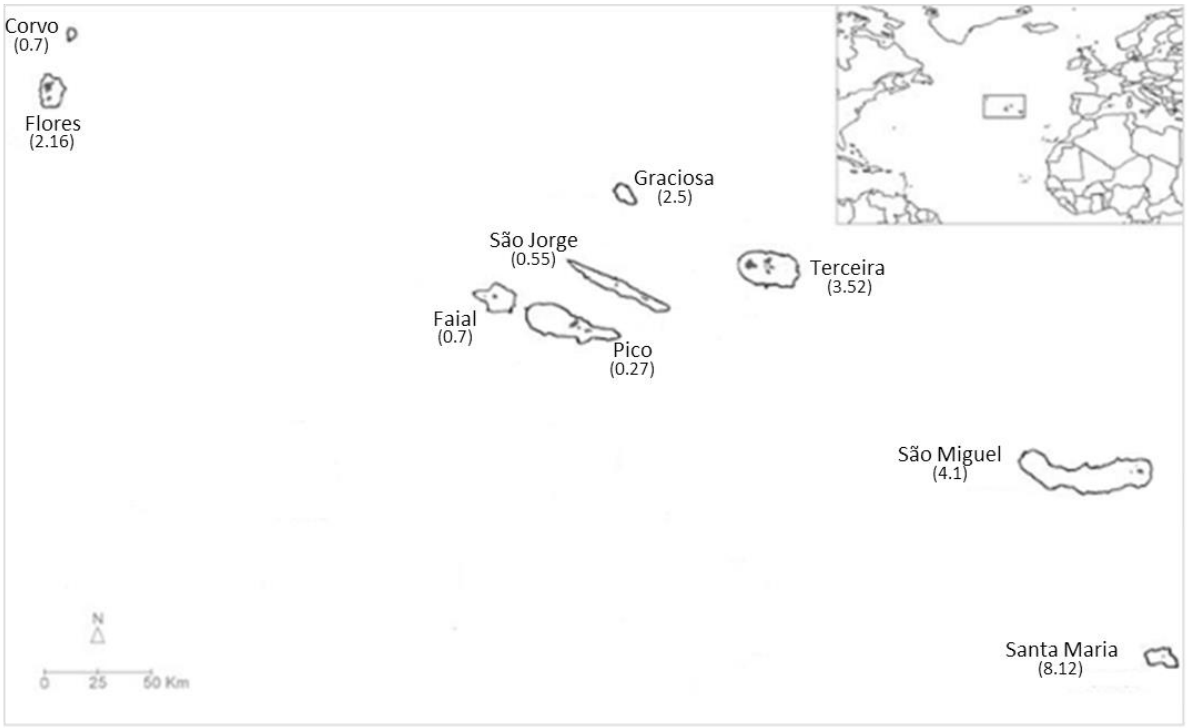

Figure 1.5 - Location of Azores in the World (on top right) and representation of the nine Islands that compose the archipelago. In black is represented the remaining native vegetation areas in each Island. Numbers bellow Islands identification represents their age in millions of years. Figure adapted from Gaspar *et al*. (2008) and from Carine & Schaefer (2010).

1.3.2. Azorean terrestrial biodiversity

Azorean islands present a unique fauna and flora, being included in the hotspot of Mediterranean biodiversity (Myers *et al*., 2000). It comprises 6489 terrestrial and freshwater taxa and 1883 marine and coastal taxa that inhabit in the archipelago (Borges *et al*., 2010). Following the pattern presented worldwide, the phylum Arthropoda presents the highest terrestrial diversity in Azorean archipelago, containing almost 40% of the taxa (Figure 1.6). Only 452 terrestrial and freshwater species and subspecies are endemic to Azores. This value represents around 7% of the total species present in the archipelago, and is mainly composed by arthropods (around 60% of the endemism – Borges *et al*., 2010). On the other hand, 70% of the vascular plant species and 58% of the arthropod species found in the Azores are exotic, and many of them are considered invasive (Borges *et al*., 2010).

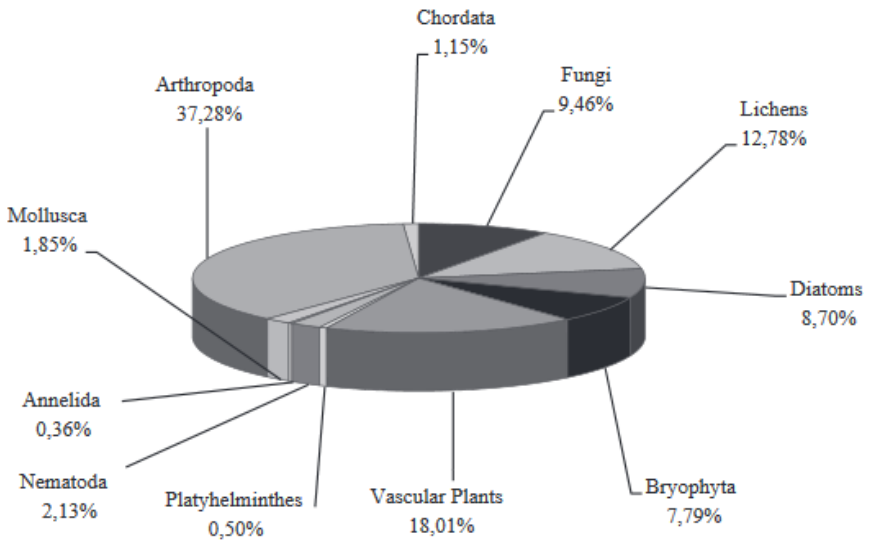

Figure 1.6 - Proportion of terrestrial and freshwater taxa (species and subspecies) from the Azores. Source: Borges *et al.* (2010).

The amount of Azorean endemisms seems to be lower than what was expected when compared with other Macaronesian Islands. In fact, the terrestrial species in Azores are about half of the known species in Canary Islands. Endemism is also in lower proportion than other Macaronesian Islands, representing only 7% of the total species in Azores, while in Canary this value is around 30% (Arechavaleta *et al*., 2010). Such difference on both the amount of biodiversity and endemism between Azores and other Macaronesian Islands (e.g. Canary and Madeira), may be justified by geographical and historical factors: area and age of the islands, distance to mainland and native vegetation destruction are important to help explaining the observed richness (Cardoso *et al*., 2010). In addition, Cardoso *et al*., (2010) anticipated that also the dispersion from mainland to Azorean archipelago is generally preceded against the wind and sea currents, dictating that only groups with high dispersal abilities can reach the Azores. Furthermore, the existence of Paleo-islands between Madeira Island and the Canary Island and the mainland is believed to have enhanced the colonization process of these Islands (Fernández-Palacios *et al*., 2011).

1.3.3 Current Climate characteristics and Climate Change

Azorean climate is temperate oceanic, and is mainly characterized by its geographic location, proximity to the ocean and the global atmospheric and oceanic circulation. The average temperature has small variations throughout the year, with a minimum of 4°C during the winter and maximum of 23°C in summer (de Azevedo, 2001; Miranda *et al*., 2006). Precipitation occurs all year long, although with less intensity in summer. The total annual precipitation is around 1700 mm. Relative atmospheric humidity mean was found to be of around 95% in the native, high altitude, semi-tropical, evergreen laurel forest.

In the Azorean archipelago, changes in precipitation and temperature have been documented for S. Miguel and Terceira Islands. For Terceira Island, the maximum temperature was found to be rising at a pace of +0.05°C/decade since 1975, while the minimum temperature is also rising, but at a

pace of +0.36°C/decade. Regarding the precipitation, it is also affected by climate change, with a significant reduction of the annual mean of -0.52mm/decade in the period between 1968 and 1993 (last year of data) (Miranda *et al*., 2006).

Recently de Azevedo & Reis (2016) regionalized a GCM, creating climatic scenarios specific to Azorean archipelago for the end of the century (Figure 1.7, but for full cartographic description see http://prac.fc.ul.pt/pt/cartografia). Similar to RCMs, these projections possess higher resolutions than GCMs. For the most severe climatic scenario, i.e., RCP 8.5, mean temperature was found to rise on almost all territory, on average 2.7°C (highest rise of 6.4°C in Pico Island). The mean temperature on Terceira Island also rises on average about 2.8°C, being the maximum rise of 4.6°C near Biscoito da Ferraria and during the summer months. Both the minimum and the maximum temperatures are also expected to increase in the same magnitude as the average temperature. Regarding the total annual precipitation, an overall decrease is expected for Azorean archipelago of around 2% by the end of the century for RCP 8.5 scenario. Spring and summer months are the most affected, with expectations to lose 7% and almost 11% of precipitation, respectively. Nonetheless, major losses in precipitation will be found in Flores Island with some areas losing more than 700 mm of precipitation. Other sites of the archipelago are also expected to increase the precipitation rate, however much less than the expected loss (de Azevedo & Reis, 2016). Notwithstanding, these projections must be interpreted with caution since extreme climatic events, such as storms with heavy precipitation, or heat waves, are likely to increase in intensity and frequency (Easterling *et al*., 2000). Figure 1.7 summarizes the current and the projected future temperature for the Azorean archipelago.

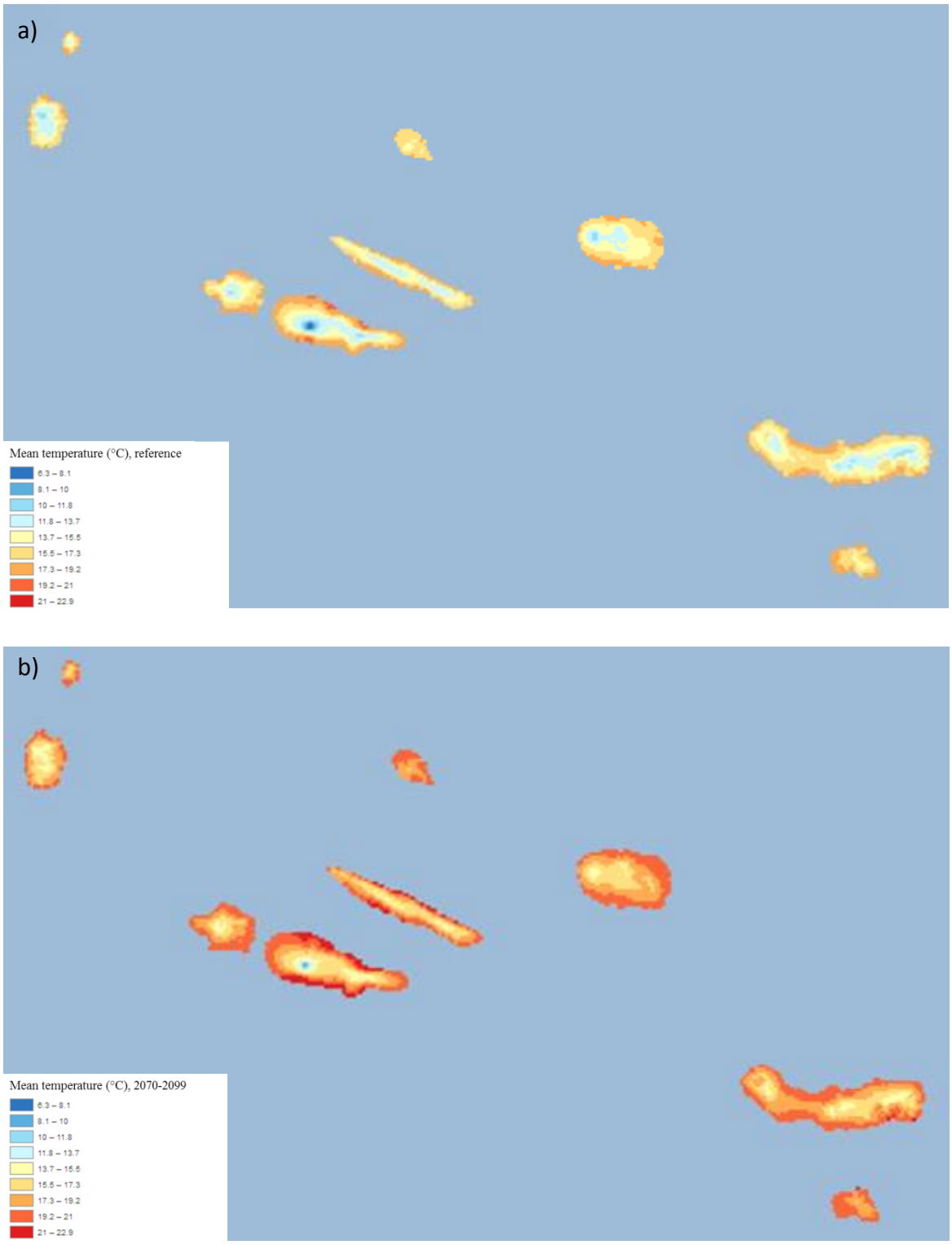

Figure 1.7 - Mean temperature for Azorean archipelago under the scenario of reference (a) and for the end of the century under RCP 8.5 scenario (b). Distances between islands are mere representations and do not correspond to the exact distance. Islands are represented at a scale of 50km. Data source: de Azevedo & Reis (2016). Adapted from http://prac.fc.ul.pt/pt/cartografia.

1.5 Modeling methods as a supportive conservation tool

Modeling techniques have proven to be useful when predicting species response to climate change (Cruz *et al*., 2016). Many functional connectivity models have been developed with a relatively easy interface in order to be applied by ecologists (e.g. Shah & McRae, 2008; Saura & Torné, 2009; Pe'er *et al*., 2011; Bocedi *et al*., 2014). Such modeling algorithms have been applied in multiple contexts: determining multiple movement paths (e.g. Lawler *et al*., 2013), gene flow among habitats (McRae & Beier, 2007), connectivity between protected areas (e.g. Mullins *et al*., 2014), potential dispersion corridors (e.g. LaRue & Nielsen, 2008), dispersal trajectories of organisms expanding their range (van Etten & Hijmans, 2010), ranking the patch importance for connectivity (e.g. Bodin & Saura, 2010), climate change influence over connectivity (Mazaris *et al*., 2013), among others. The majority of these studies are conducted with one of two algorithms: Circuit-theory (Shah & McRae, 2008) and Least-cost Path (LCP) (Adriaensen *et al*., 2003). Also, Dispersal Paths (van Etten, 2015), a recent modeling method, appears to be emerging in use within the scientific community. All these methods require the production of a resistance map, which reflects the difficulty that different land-uses offers to individuals movement. Thus, each species modeled require its own resistance matrix. However, there are some important differences between these methods that need to be considered.

LCP technique models the relative cost for an individual to move between two areas of interest (i.e. suitable habitats, populations, etc.), producing the path with the least costly distance between two areas under study. In theory, LCP will contain the most suitable habitat with the fewest movement barriers (Larkin *et al*., 2004), representing the best route possible for a dispersing individual. However, LCP assumes that individuals have complete knowledge over the landscape they are in, being capable of follow the least costly path. This is an unrealistic assumption (Coulon *et al*., 2015).

Circuit-theory brings into ecology concepts from electricity, relying on Ohm's law, where a voltage (source of dispersion – population) is applied across a resistor (landscape), resulting in a certain current flow (connectivity) (McRae *et al*, 2008). More detailed, current flow can be interpreted as the expected net movement probability for random walkers to move through certain site. Like in an electric flow (when in a heterogeneous circuit), the current flow spreads through the landscape, generating multiple paths between the two areas of interest (McRae *et al*, 2008). Thus, unlike LCP, it incorporates several possible paths. Notwithstanding, unless in presence of absolute barriers (e.g. large rivers, highways, etc.), current will flow always throughout the landscape, even if the habitat is considered inhospitable, resulting always in some connectivity.

Similar to circuit-theory, Dispersal Paths is used to evaluate the dispersal paths of a random walk generated in a given location (van Etten, 2015). Individuals will then disperse to a known local, and a matrix of possible paths is generated. Like in the previous case, dispersal paths always generate paths, independently if in the presence of inhospitable environment (unless if impermeable barriers are identified).

Generally, all the models described above provide a very simplistic analysis of functional connectivity, since it is not based on behaviorally realistic movement rules (Coulon *et al*., 2015). Moreover, none of these models is capable of incorporating other complexities that can affect species ability to disperse (e.g. life-cycle, interactions among species, reproduction, mortality, etc.).

To face such difficulties, other modeling methods have emerged. This is the case of Agent-Based Models (ABMs). ABMs are a computational simulation method that recognizes individual

agents in a given landscape, where individual variability, local interactions and adaptive behavior can be considered (Railsback & Grimm, 2011). ABMs rely on a bottom-up approach that explicitly contemplates the components of a system (i.e. individuals as agents and landscape units as cells). Each agent interacts in an autonomous and different way with the surrounding environment and with other agents, becoming more complex than other modeling techniques, and ultimately allowing to address and better understand many other research questions (DeAngelis & Mooij, 2005; Railsback & Grimm, 2011). For these reasons, ABMs were dubbed as the 'third way' of doing science (Axelrod, 1997).

ABMs flexibility have allowed them to be widely applied in multiple ecological contexts (see DeAngelis & Mooij, 2005 for detailed description), ranging from road ecology (Ascensão *et al*., 2014), design or redesign of protected areas for species conservation (Moustakas, 2016), populations' dynamics (Arifin *et al*., 2014), or even toxicity consequences for animals survival (Pavlova *et al*., 2015). Although recognized as a valuable tool in connectivity research (Barton *et al*., 2009), this modeling method has been narrowly applied for such purpose. Nonetheless, ABMs are seen as a versatile tool that can have an important role to play in modeling animal behavior and movements for wildlife-management objectives. For these reasons, ABMs '*can be useful to scientists, managers, decisions makers, and even the general public*' (McLane *et al*., 2011).

Like any modeling method, this also possesses some difficulties that can challenge its implementation: it requires that the modeler possesses some programming skills and usually requires huge amount of parameters that can only be achieved with data; such complexity can result on highly time-consuming simulations (Coulon *et al*., 2015).

1.6 Thesis Framework

The present thesis is inserted in the Masters' program on Ecology and Environmental Management, provided by Faculdade de Ciências da Universidade de Lisboa (FCUL). It was developed within Climate Change, Impacts, Adaptation and Modeling (CCIAM) research group, Centre for Ecology, Evolution and Environmental Changes (cE3c). The present thesis was developed under the scope of Regional Plan for Climate Change of Azores (PRAC) project, conducted by an inter-disciplinary research team, where the CCIAM research team was responsible for the Ecosystems and Natural Resources sector.

1.7 Thesis objectives

My thesis's objectives included:

i) The development of an Agent-Based Model (ABM) able to simulate movement across a given landscape, and apply it to 5 ground-dwelling Azorean endemic species in Terceira Island;
ii) Compare our developed ABM with the known and widely used modeling techniques: Circuit theory, Least-Cost Path, and Dispersal Paths;
iii) Use the ABM to understand how species use the area available;

iv) Use the ABM to investigate the existence of corridors between native vegetation areas, and based on this results, suggest areas of management action;
v) Use the ABM to investigate how climate change will impact the use/effectiveness of such corridors;
vi) Use the ABM to evaluate the effect of recently restored areas regarding functional connectivity among native sites.

1.8 Thesis structure

The present thesis is structured as follows:

- General Introduction
- One manuscript presenting results on ABM modeling
- One manuscript presenting results of an application of ABM
- General discussion

Chapter 2 – Climate Change implications on landscape functional connectivity: a case study with insects in Terceira Island (Azores)

Aparício BA[1], Cascalho J[2], Cruz MJ[1], Borges PAV[3], Azevedo EB[4], Elias RB[3], Ascensão F[5,6]

1 – cE3c – Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal

2 – Núcleo de Investigação e Desenvolvimento em e-Saúde (NIeS), Universidade dos Açores, 9700-042 Angra do Heroísmo, Terceira, Azores, Portugal

3 – cE3c – Centre for Ecology, Evolution and Environmental Changes / Azorean Biodiversity Group and Universidade dos Açores, Faculdade de Ciências Agrárias e Ambiente, 9700-042 Angra do Heroísmo, Terceira, Azores, Portugal

4 - Centre of Climate, Meteorology and Global Change of the University of the Azores (CCMMG-CITA-A). Departamento de Ciências Agrárias, Universidade dos Açores, 9700-042 - Angra do Heroísmo, Portugal

5 - CIBIO/InBio, Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto. Campus Agrário de Vairão, Vairão, Portugal

6 - CEABN/InBio, Centro de Ecologia Aplicada "Professor Baeta Neves", Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

Corresponding author: Aparício BA, email: bruno.a.aparicio@gmail.com

2.1 Abstract

Species distribution models (SDMs) have been widely developed and applied to predict suitable areas for species to inhabit, under current and future climatic conditions. However, such modeling effort usually incorporates only climatic data, overlooking crucial physical factors, such as land-use information.

In this study, we developed an Agent-based model (ABM) that incorporates multi-species movement parameters. We apply it to five ground-dwelling Azorean beetles insects in Terceira Island, Azores, and produce a regional connectivity map for each species. This connectivity map is then faced against the climatic suitable areas derived from an SDM to evaluate movement capacity within such area. Sites most used for species movement are named 'quality' areas. Furthermore, we analyze important sites where restoration would increase functional connectivity among habitats.

Our results showed that projected climatic suitable areas are not equally used by species in their movement. Quality areas were found to be expressively in lower area than projected suitable areas (highest decrease of 94%). We further observed a continuous decrease in 'quality' areas from current to future climatic conditions, indicating that reductions in climatic suitable areas also occur in highly important areas for movement behavior. We identified locals near Biscoito da Ferraria and Matela as priority for restoration.

We showed that functional connectivity can be severely reduced by climatic change. We further recommend land-use information to be included in SDMs projections (as a proxy of connectivity). If not, studies can underestimate real species vulnerability to climate change.

Keywords: Climate change adaptation, Connectivity, Corridor design, Landscape management, Agent-Based Model, Island ecology, Circuit-theory, Oceanic Islands

2.2 Introduction

Habitat fragmentation, habitat degradation (e.g. due to invasive species) and climate change effects represent main stressors for biodiversity (Sala *et al*., 2000; Gitay *et al*., 2002; Parmesan, 2006; Rosenzweig *et al*., 2007), and their impact is expected to increase significantly in near future (Maxwell *et al*., 2016). While the intensification of human land-uses (e.g. through agriculture intensification) is diminishing the available habitat for many species (Fischer & Lindenmayer, 2007), the changes in climate are expected to alter the current ecological conditions which may severely affect the spatial distribution of habitat for numerous species (Mawdsley *et al*., 2009; Bellard *et al*., 2012). Overall the quality and availability of habitat is decreasing while the climatic optimum is shifting (Garcia *et al*., 2014), forcing wildlife to track best environmental conditions through landscapes with fewer and more isolated habitat patches (see Chen *et al*., 2011; McGuire *et al*., 2016).

In Islands, the effects of climate change over the biota are expected to pose a more extreme pressure. Islands are usually small, have already reduced original native habitats, and sea level rise is expected to submerge significant areas, leading to a decrease of species richness and population size (Mawdsley *et al*., 2009; Wetzel *et al*., 2013; Courchamp *et al*., 2014). Also, islands harbor a high number of endemic species (Kier *et al*., 2009), which usually have low dispersal ability, hindering their migration to new suitable areas. Furthermore, due to high levels of deforestation that islands usually possess (Borges *et al*., 2005; Triantis *et al*., 2010), such sites may become unreachable (Courchamp *et al*., 2014).

The distribution of species generally results from the reunion of suitable environmental conditions that allow the individuals to fulfill their basic needs, e.g. shelter, food and reproduction (Matthews *et al*., 2011; Brambilla & Ficetola, 2012). Both climate and land-use are two interrelated primary driving forces of species distribution as they influence significantly the localization of suitable areas for species' occurrence (Pearson & Dawson, 2003; Thuiller *et al*., 2004). Species distribution models (SDMs) are one of the most important tools currently available to assess the potential impacts of these global change stressors and delineate conservation management practices (Jones *et al*., 2016). Such models have been widely used not only to model current species distributions, but also to forecast species distribution for the future by incorporating different scenarios of climatic conditions (see e.g. Araújo *et al*., 2011; Ferreira *et al*., 2016). However, land-use information is seldom used when producing SDMs (Barbet-Massin *et al*., 2012). Yet, incorporating this information can lead to significant changes of forecasted suitable areas (Vos *et al*., 2008; Sohl, 2014).

Landscapes with higher functional connectivity, i.e. '*the degree to which the landscape facilitates or impedes movement among resource patches*' (Taylor *et al*., 1993), allow regular movements of individuals across the regions and consequently of gene flow, ultimately reducing the probability of extinction (Krosby *et al*., 2010). Moreover, connectivity is critical for species to track rapidly changing climates (McGuire *et al*., 2016). Hence, it is essential to identify the most important sites to maintain or reestablish the functional connectivity. However, if the effects of land-use are overlooked, conservation efforts targeting climate change effects can be undermined (Loiselle *et al*., 2003). Nevertheless, how land-use and climate change effects translate into functional connectivity is generally unevaluated (but see also Elmhagen *et al*., 2015).

Connectivity is usually measured recurring to computational algorithms. However, the majority of the used algorithms rely on too simplistic simulations. For instance, circuit-theory and Least-cost path, two of the most used simulations, considerate the connectivity as a never-ending flow that, if in the absence of complete barriers, always reach the target site, independently from the site

inhospitality (McRae *et al*., 2008). Although useful and applicable to a large set of studies, such algorithms lack from behaviorally realistic movement rule, as 'individuals' have full knowledge of the landscape they are in (see Coulon *et al*., 2015). Such limitations can be overcome by resorting to Agent-Based Models (ABM). ABMs are capable of recognizing individual agents in a given landscape, where individual variability and local interactions can be considered. By relying on a bottom-up approach that explicitly contemplates the components of a system, the movement pattern that emerges is the result of multiple individuals' choice, rather than a simple flow of current (Railsback & Grimm, 2011; Coulon *et al*., 2015). However, only recently an ABM was developed to evaluate functional connectivity (see Allen *et al*., 2016).

In the present study, we developed a simple ABM simulating random walks conditioned by land-use resistance, slope and mortality, and applied it to five ground-dwelling endemic insects inhabiting Terceira Island, from Azores archipelago. Previous research on climatic-based distribution models suggests high reductions and shifts in species distribution in near future (Ferreira *et al*., 2016). In fact, it is estimated ca. 50% (n=270) of endemic arthropod species and subspecies inhabiting Azorean native vegetation might be driven to extinction (Triantis *et al*., 2010), which correspond to ca. 60% of the known terrestrial endemism in Azores (Borges *et al*., 2010). Moreover, due to the restricted available land, pressure between different land-uses can further compromise conservation initiatives.

The main goal of this study was to detect important areas of functional connectivity including key areas to allow animal movement between areas of native vegetation. The model is spatially explicit, adjustable and parameterized, so that different landscapes and species attributes can be displayed and studied. Hence, we anticipate that this study will be useful to both conservation planners and ecologist and conservation researchers, who seek to understand species movement and dispersal.

2.3 Material and Methods

2.3.1 Study area

The Azorean archipelago is located in the North Atlantic (37° to 40° N latitude and 25° to 31° W longitude). It is composed by nine Islands, with a total area of 225,000 hectares. The present study was focused on Terceira Island, the third biggest island of the archipelago, with approximately 40,200 hectares (Figure 2.1). The land-use in Terceira is composed mainly by intensively managed grasslands (ca. 30%) and ca. 14% of native vegetation. This native vegetation in Terceira is dominated by "Laurus Submontane Forests", "Juniperus-Ilex Montane Forests" and "Juniperus Montane Woodlands" (Elias et al., 2016). Laurisilva is a humid evergreen broadleaf forest composed by Laurus azorica, All these forest types are luxuriant and include bryophyte communities and several species of sclerophyllous, and microphyllous trees and shrubs (Gabriel & Bates, 2005; Elias *et al*., 2016). This ecosystem is known to harbor most of the endemic species from Azores, and seems to act as a barrier to invasive species proliferation (Cardoso *et al*., 2009; Cardoso *et al*., 2011; Florencio *et al*., 2016). Moreover, Terceira Island harbors the most well preserved "Juniperus-Ilex Forests" and "Juniperus Woodlands" of Azores (Gaspar *et al*., 2011).

The climate is temperate humid at sea level and cold oceanic at higher altitudes. The atmospheric humidity is high with small temperature fluctuations throughout the year, and can reach 95% of annual average in the native high altitude semi-tropical evergreen laurel forest. Maximum and

minimum temperatures in Terceira are rising at a rate of 0.05°C and 0.36ºC per decade, respectively (data from 1975 to 2002; Miranda *et al*., 2006). It is expected that under the RCP 8.5 scenario (van Vuuren *et al*., 2011), in 2100 the temperature will be on average 2.7°C higher and the precipitation lower by 35 mm (de Azevedo & Reis, 2016).

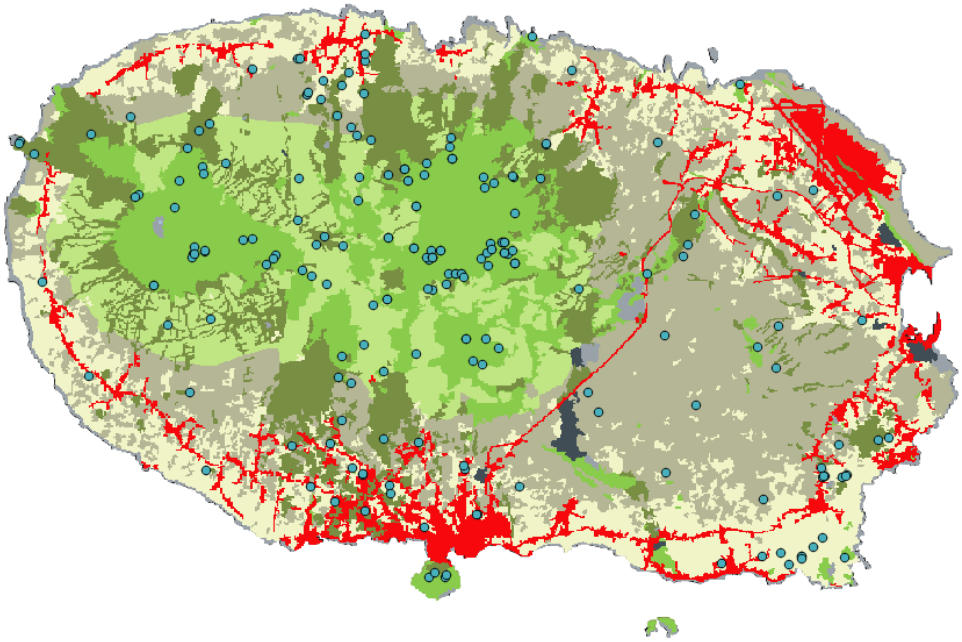

Figure 2.1 - Terceira Island land-use information. Urban sites (red) and agriculture (light brown) occupy the periphery of the Island, while intensive grasslands (dark brown), exotic forest (dark green), semi-natural grasslands (light green) and native vegetation (something green) are mainly located in the interior of the Island. Some industrial areas (grey) are also identified. The remaining land-uses (i.e. lagoons and open areas) occupy small areas and are not visible in the figure. Dots represent the sampled transects (n=182).

2.3.2 Model species

Five ground-dwelling species were selected, covering a gradient of dependence of native vegetation (from specialists to more generalist, regarding the habitat): *Trechus terrabravensis* Borges, Serrano & Amorim, 2004 (Insecta, Coleoptera, Carabidae), *Cedrorum azoricus azoricus* Borges & Serrano, 1993 (Insecta, Coleoptera, Carabidae), *Drouetius borgesi borgesi* Machado, 2009 (Insecta, Coleoptera, Curculionidae), *Aphrodes hamiltoni* Quartau & Borges, 2003 (Insecta, Hemiptera, Cicadellidae) and *Alestrus dolosus* (Crotch, 1867) (Insecta, Coleoptera, Elateridae). *Trechus terrabravensis* and *Cedrorum azoricus azoricus* are predatory ground-beetles living in the soil and restricted to hyper-humid Laurus Submontane Forests", "Juniperus-Ilex Montane Forests in ravines (Borges *et al*., 2006). *Drouetius borgesi borgesi* is a weevil that during the night eats the leaves of several endemic trees (e.g. Laurus azorica) (Machado, 2009). *Aphrodes hamiltoni* is a phytophagous insect that lives in the soil litter and feed on endemic grasses (Quartau & Borges, 2003). *Aletrus dolosus* is a click-beetle that lives associated with the bark of *Juniperus brevifolia* occurring also in open areas of semi-natural

pastures. The choice of such species allowed us to study and evaluate a wider range of organisms' types. The suitable areas (SDMs) to the five species were previously projected by Ferreira *et al*. (2016) for both current (1961-99) and future climatic conditions (2080-99). Projections for future climatic conditions were assessed under Representative Concentration Pathways (RCP) 8.5, the most severe but yet realistic scenario of climate change (van Vuuren *et al*., 2011).

2.3.3 Agent-based model

We developed an agent-based model simulating the insects' movement based on random walk conditional on probability of use and mortality probability. The model requires two raster layers to derive the probability of use: land-use and slope. We used the most recent land-use information available, and a resolution of 100 meters (DROTRH, 2008). The layer was further corrected from field work observations to include information regarding the localization of semi-natural and intensive pastures (Gaspar, unpublished data). The slope was obtained from the digital elevation model (USGS, 2016), using the QGIS Slope tool (QGIS, 2016), also with a 100 m resolution. The land-use was converted into species-specific resistance values based on expert knowledge from one of us (Borges, P.A.V). A slope threshold was also derived from expert knowledge (see Table 6.1). For each cell, a probability of use (*P*) was then calculated:

$$P = \frac{1}{1 + \left(\frac{s}{t}\right)^{k}} \times \frac{1}{r}$$

(eq.1)

where *s* represents the slope; *t* represents the species' specific slope threshold; *k* is a constant value (here we used of 5) and represents the importance that slope has for each species; and *r* is the resistance to movement of the land-use class. The probability of mortality for each cell (*M*) was calculated as follows:

$$M = \frac{r}{m}$$

(eq.2),

where *m* represents a qualitative mortality parameter. Because mortality in different land-covers can be difficult to estimate (Beier *et al*., 2011), here we used three different levels for *m* (1000, 10000 and 50000, representing high, intermediate and low mortality, respectively). These values were chosen taking into consideration the lowest value that allowed dispersion and the maximum value that allowed reasonable computation time. The intermediate value was chosen to provide an intermediate mortality when compared with the extreme values. By setting three levels of mortality (two of them extreme), we expect to capture multifaceted aspects of uncertainty.

Before simulations, the model identifies the clusters of native vegetation present in the landscape, allowing to track the amount of individuals that disperse among these clusters. The model can also import SDMs from the focal species, which can be used to restrain agent spread throughout the territory. When a simulation starts, insects are set to move according to the probability of use following a weighted probability. Insects (agents) move one step at a time, to one of the neighbors. When arriving to a new neighbor, insects will die according with the probability of mortality (*M*).

However, to avoid loop movements, the probability of use for a used patch becomes zero. So the chance for agents to step into the same patch is diminished.

Two types of simulations were run. In the first, agents are spread randomly throughout the island and they move across the landscape until their death. Each patch registers each unique insect that stepped into it, and after a sufficient number of agents being launched (in our case we chose 10 million, per species), we obtain a map where the movement is more likely to occur, for a given set of values of land-use resistance, slope and mortality. We called this the connectivity map. In the second simulation type, we started by generating one agent in every patch in the edge of all clusters of native vegetation inside the SDM. Again, when agents are moving, each patch registers the identities of insects that stepped into it, except that this information is retain only from those insects that successfully reach a different cluster. In addition, the number of agents that each cluster receives is also recorded. This simulation type was run using the SDM for the present and with SDM for the future. This second simulation type allows detecting important areas for maintaining or improving the functional connectivity between pristine areas (clusters).

The model was developed in NetLogo (Wilensky, 1999) and the terminology here used is in accordance to the software language (e.g. agent, patch). See the ODD protocol (in Chapter 6 Supplementary Materials, Section 6.1.2.1) for fully description of the model.

2.3.4 Identifying important areas for functional connectivity

We used the connectivity maps obtained from the first simulation type to highlight the cells inside the SDM that are more likely to be used by moving individuals. We classified these areas into three classes according to the number of insects that used them: 'medium quality', for those cells with a use within the percentiles 75-85%; 'high quality', for those cells with a use value within the percentiles 85-95%; and 'top quality', for those cells with a use higher than percentile 95%. The use of such classification was meant to identify priority areas for connectivity. From the outputs of the second simulation type we identified the most important sites to restore between pristine areas, i.e. key stepping-stone cells. For each cell outside the native vegetation clusters we calculated the importance (*I*) as follows:

$$I = \frac{\log(u + 1)}{d^{-2}}$$

(eq.3)

where *u* is the use of the cell (i.e., the number of different agents that having reached a different cluster used that cell), and *d* represents the distance of the cell to the nearest cluster. We further considered only those cells with an importance *I* over the 95% percentile of all cells' importance. We also derived the multi-specific priority stepping-stones by overlaying the resultant maps across species.

2.3.5 Model validation and sensitivity analysis

We produced 1000 random combinations of land-use resistances and slope thresholds (generating random probabilities of use) and repeated the first simulation type. In order to ensure the creation of such amount of random combinations and maintain the computational time reasonable, we limited the

number of insects generated to 100.000. Also, connectivity maps that used expert-knowledge for this step were generated with the same amount of insects, allowing comparability between resistance matrixes. The comparisons were assessed using an existing dataset of presence-absence of these species to test the robustness of our model. The dataset consisted in captures by pitfall traps in 182 unique sites throughout the island, surveyed for over 10 years (Borges *et al*., 2005). The data was aggregated in a way that all sites with at least one presence were coded as 1 and 0 otherwise (number of presences for each species: *Alestrus dolosus* = 22; *Aphrodes hamiltoni* = 76; *Cedrorum azoricus azoricus* = 26; *Drouetius borgesi borgesi* = 23; *Trechus terrabravensis* = 16). Binomial generalized linear models (GLM) were used to relate the presence/absence data with the connectivity maps, i.e. with the number of unique agents stepping the cells where the pitfalls were set. We assumed that occupancy of a given site was related to the likelihood of being used for movement, i.e. areas of higher functional connectivity would also have higher probability of occurrence. Hence, the McFadden's pseudo R^2 values of each model were compared, expecting that the GLM using the expert knowledge would provide higher goodness-of-fit.

We used the same approach to compare the connectivity maps from our ABM (fed with expert-knowledge) with those produced by three other commonly used algorithms for studying functional connectivity: circuit-theory (McRae *et al*., 2008), least-cost path (Adriaensen *et al*., 2003), and dispersal paths (van Etten, 2015). Because the ABM integrates mortality probabilities, and hence is more biological realistic, we expected that it would outperform those algorithms.

To assess how the results could vary with different values for mortality (*M*) parameter, we also used the same approach to compare the fit of the connectivity maps with the three levels of mortality. If a close performance was found when using extreme, yet plausible, mortality levels, then we could assume that the ABM was not very sensitive to changes in *M* and therefore the uncertainty was reduced. All analyses and plots were made in R environment (R Core Team, 2015).

2.4 Results

2.4.1 Model validation

The connectivity maps generated based on expert knowledge (Figure 6.1 to Figure 6.5) proved to outperform those using randomly assigned resistances for all species. The best results were obtained for *Alestrus dolosus*, *Aphrodes hamiltoni* and *Drouetius borgesi borgesi*, for which we obtained a fit higher to 98% relatively to the random models (Table 6.4). This result supported the use of resistance based on expert knowledge. Regarding the other algorithms tested, the ABM also had a higher fit, particularly for *Aphrodes hamiltoni* (Table 6.5), supporting the use of our ABM for further modeling analyses. Furthermore, the sensitivity analysis revealed that the model was not significantly sensitive to changes in the mortality parameter (Table 6.6). In fact, the highest difference of R^2 when using the extreme levels of mortality was 6% (for *Cedrorum azoricus azoricus* and *Trechus terrabravensis*). For this reason, we decided to use the intermediate mortality level in further simulations.

2.4.2 Suitable areas vs quality areas

We detected for all five species that connectivity quality areas covered a considerable lower area when compared to the suitable area derived from SDMs (Figure 2.2). For both timeframes, medium quality areas were mostly located in semi-natural pastures and exotic forests, although with low or no expression in *Cedrorum azoricus azoricus* and *Trechus terrabravensis*; whereas high and top quality areas were restricted to native vegetation areas (Figure 6.6 to Figure 6.10). For current conditions, this reduction was over 60% for *Alestrus dolosus* and *Trechus terrabravensis* (Figure 2.2). Furthermore, under future climatic conditions, those species with already little projected suitable areas will have their quality areas further reduced. The most severe case was found to belong to *Trechus terrabravensis* for which only just 10 hectares are expected to remain of higher quality (corresponding to a reduction of 94%).

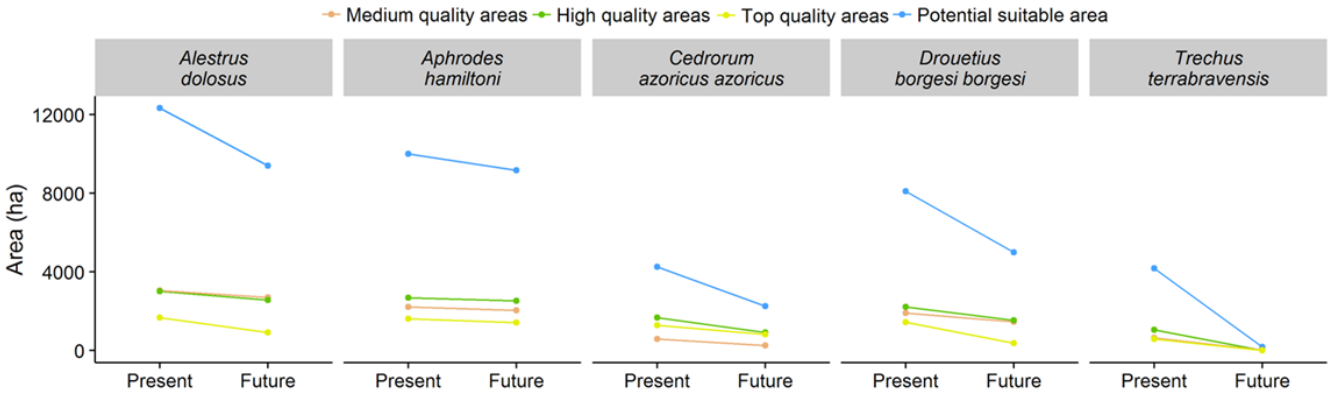

Figure 2.2 - Amount of suitable area available per species (in hectares) projected by the SDM for current and future climatic conditions (blue line) and the amount of quality area that is projected by the ABM: medium quality (yellow line), high quality (orange line) and top quality (green line).

2.4.3 Identification of the existent corridors between native vegetation areas

Under the current climate, all species but *Cedrorum azoricus azoricus* showed a relatively high capacity to exchange individuals among native sites, being *Alestrus dolosus* the species with the highest dispersal capacity (Table 2.1). Under the future climate scenario, *Alestrus dolosus* and *Aphrodes hamiltoni* were found to maintain their ability to disperse to other native sites. On the other hand, *Cedrorum azoricus azoricus*, *Drouetius borgesi borgesi* and *Trechus terrabravensis* presented severe reductions in the number of individuals that disperse to another native site. This decrease in the number of dispersals is most evident for *Trechus terrabravensis* and *Cedrorum azoricus azoricus*, which under future climate reduced their dispersals to ca. 2% and 11% of the total number of dispersals under the current climate (Table 2.1). The native areas located near Biscoito da Ferraria (in the Center-East) were found to be the best connected areas for all species. Serra de St. Bárbara was found to be mainly isolated for the majority of the studied species (Figure 6.11 to Figure 6.15).

Table 2.1 - Total number of individuals in all model runs per species and per climatic scenarios that are able to reach a new native vegetation site different from the one where they were generated.

	Alestrus dolosus	***Aphrodes hamiltoni***	***Cedrorum azoricus azoricus***	***Drouetius borgesi borgesi***	***Trechus terrabravensis***
Current climate	42246	35426	3255	38037	35551
Future climate	45935	36623	350	26449	540
Change	+ 9%	+ 3%	- 89%	- 30%	- 98%

Regarding the identification of the prioritized locals for ecological restoration, we found them to be mainly located around the southern part of Biscoito da Ferraria (with the occurrence of the five species for present climatic conditions and four for future climatic conditions). Other relevant local identified is between Serra de St. Bárbara and Biscoito da Ferraria and near Matela. Generally, the location of such priority sites remained the same between present and future climatic conditions (Figure 2.3). These results can be visualized with the help of the files in https://drive.google.com/open?id=1JQ3grNzBJK95w7vJG_ZOl1XqpSE&usp=sharing.

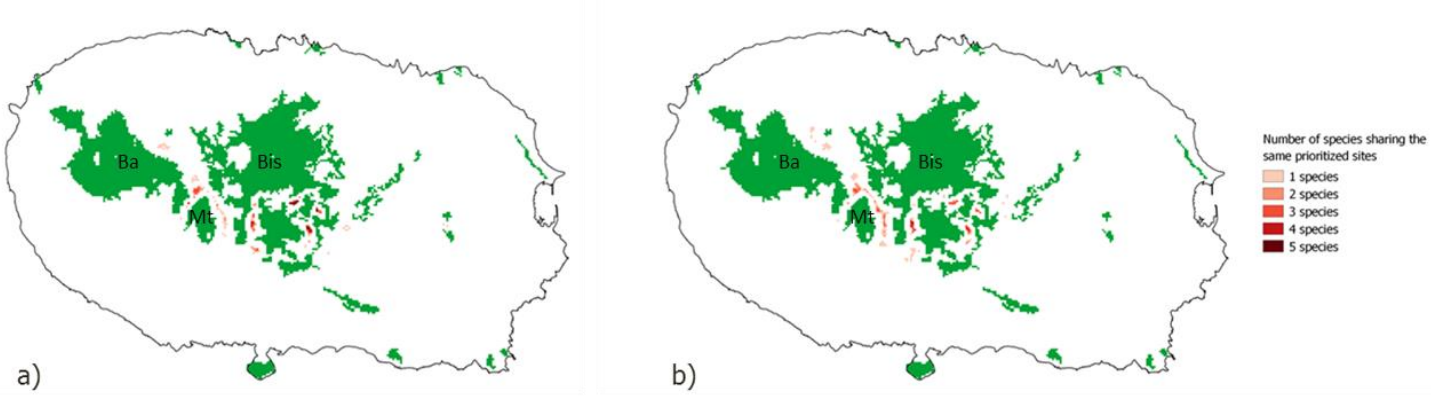

Figure 2.3 - Localization of the priority areas for the studied species, under current (a) and future (b) climatic conditions. Darker red indicates that the local was considered as a priority for more species. Native vegetation sites are represented at green. Serra de St. Bárbara (Ba), Biscoito da Ferraria (Bis) and Matela (Mt) are identified in the figure.

2.5 Discussion

Our results showed that functional connectivity can be heavily compromised under climate change effects. According to our simulations, the area with higher likelihood of being used for animal movement currently occupies a small proportion of the predicted suitable area by SDMs. Furthermore, the projected reduction of the suitable areas will further reduce higher quality areas for functional

connectivity. Ferreira *et al*. (2016) anticipated that around 14% of the studied Azorean arthropods species will lose between 90% and 100% of their suitable areas by the end of the century. Here we show that connectivity in quality areas will likewise suffer significant reductions, reaching an alarming value of 94% for *Trechus terrabravensis*. Overall, our results show that functional connectivity will be significantly reduced by climate change for all the species. Assuming that other small sized species in Azores face similar threats (Cardoso *et al*., 2013), our results suggest that a great proportion of those species will lose almost all their high quality areas for movement. Therefore, species range shift, as a response for climate change effects, can be seriously compromised.

Using the ABM we were able to produce connectivity maps that outperformed three commonly used connectivity algorithms. This was probably due to the inclusion of a mortality parameter in our model, which lacks in the other algorithms. In fact, the lower value fit by circuit theory, least cost paths and dispersal Paths were found for *Cedrorum azoricus azoricus* and *Trechus terrabravensis*, the two most threatened species from the set. *Trechus terrabravensis* inhabits exclusively very humid laurel forests, with high cover of mosses and ferns (Borges *et al*., 2004, 2006); while *Cedrorum azoricus azoricus* is mainly found in major autochthonous plant community area of Azores (Borges & Serrano, 1993), particularly in ravines (Borges *et al*., 2006). Conversely, *Aphrodes hamiltoni* and *Alestrus dolosus* are common and less specialist species regarding the habitat (Quartau & Borges, 2003; Nardi & Mico, 2010). Hence, by restricting the movement according to species sensitivity to land cover preferences, we were able to add more realism to our simulations. Nevertheless, our model is very simplistic and adding other components of species' biology, movement and population dynamics (e.g. reproduction), would probably improve the robustness of results (e.g. Avendaño-Mendoza *et al*., 2005; Arellano *et al*., 2008; Roslin *et al*., 2009). However, it was our goal to use a simple yet realist model that could be used for studying other species in other environments. Moreover, the scarcity of data on our model species (and generally of Azorean arthropod fauna), hampered the parameterization and inclusion of such components in the model. In fact, the model parameterization relied on expert knowledge. One may argue that the quality of expert-based information may vary substantially depending on personal beliefs and experiences (Martin *et al*., 2012). However, the expertise of one of us (Borges, P.A.V) is based on decades of intensive study and fieldwork in Azorean islands, and therefore is probably one of the researchers with higher knowledge in these species. Therefore, we are confident that the information provided is accurate. Moreover, the model validation procedures suggest that our framework was robust.

The most important areas to restore are located near Biscoito da Ferraria. These sites should be considered for future restoration, as they were classified as priority for the majority of species (five and four for current and future climatic conditions, respectively). Other important sites to restore are located near Matela, and could be an important local to enhance the connectivity among Serra de St. Bárbara, Biscoito da Ferraria and Matela. Borges *et al*. (2000) prioritized Serra de St. Bárbara and Serra dos Biscoitos against other 14 native forest reserves in the Azorean archipelago, on the basis that both areas host a high amount of arthropod biodiversity, being Serra de St. Bárbara the most well preserved reserve in the Azorean Archipelago (Gaspar *et al*., 2011). Ensuring connectivity between these areas would not only allow the migration of individuals as a response to climate change (McGuire *et al*., 2016), but because the majority of the native fragments possess exclusive arthropods species, connecting the native fragments would also allow the dispersion of unique species (Gaspar *et al*., 2011). As suggested elsewhere, exotic forests and semi-natural pastures could act as corridors to ensure the dispersal of some endemic and native species (Cardoso *et al*., 2009). However the importance of such areas for overall connectivity of the island should not be overlooked, these areas

are unlikely to provide sufficient functional connectivity for more restrict and specialists species (here showed by *Cedrorum azoricus azoricus* and *Trechus terrabravensis*). By creating stepping-stones or corridors between native vegetation areas we can shorten the distance between these areas. Shorter distances enhance the probability of dispersers to find patches by diminishing the time required by dispersals to travel through non-native matrix, minimizing their exposure to the threats (Williams *et al*., 2005; Niebuhr *et al*., 2015). Such landscape improvements would be particularly important for *Trechus terrabravensis* and *Cedrorum azoricus azoricus*. It should be noted that some of the required changes are already taking place (IMPACTBIO, 2016), but more is probably needed.

The method that we presented here can be a useful tool to a decision-making process, as it can be easily used to generate scenarios of conservation and to validate adaptation options (e.g. planned reforestation), leading to a more informed and useful discussion among stakeholders (Aparício *et al*., in prep.a).

2.6 Acknowledgements

We would like to thank the anonymous reviewers that helped improve the quality of this manuscript. A special thanks to Pedro Neves and David Avelar, for facilitating the computational resources that significantly reduced the simulation time; Rita Godinho, for all the help and GIS support; and Luís Borda de Água for all the discussion and helpful comments. This project was partially financed by FCT Unit funding (Ref. UID/BIA/00329/2013).

Chapter 3 - Implications of recent reforestations in Terceira Island (Azores) for functional connectivity – An application of a new Agent-based model

Authors: Aparício BA[1], Ascensão F[2,3], Cascalho J[4], Borges PAV[5], Azevedo EB[6], Elias RB[5], Cruz MJ[1]

1 – cE3c – Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal

2 - CIBIO/InBio, Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto. Campus Agrário de Vairão, Vairão, Portugal.

3 - CEABN/InBio, Centro de Ecologia Aplicada "Professor Baeta Neves", Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal.

4 – Núcleo de Investigação e Desenvolvimento em e-Saúde (NIeS), Universidade dos Açores, 9700-042 Angra do Heroísmo, Terceira, Azores, Portugal

5 – cE3c – Centre for Ecology, Evolution and Environmental Changes / Azorean Biodiversity Group and Universidade dos Açores, Faculdade de Ciências Agrárias e Ambiente, 9700-042 Angra do Heroísmo, Terceira, Azores, Portugal

6 – Centre of Climate, Meteorology and Global Change of the University of the Azores (CCMMG-CITA-A). Departamento de Ciências Agrárias, Universidade dos Açores, 9700-042 - Angra do Heroísmo, Portugal.

Corresponding author: Aparício BA, email: bruno.a.aparicio@gmail.com

3.1 Abstract

Current conservation actions struggle to positively impact biodiversity, as landscape is continuously being impacted by human activities. This has led to many protected areas to become isolated from other natural sites, which can pose a threat to species survival under a scenario of climate change.

In this study, we applied a recently developed Agent-based model (ABM) that simulates animal movement to five ground-dwelling Azorean insects in Terceira Island, aiming to assess the functional connectivity between two of the most important natural reserves in Azores (Serra de St. Bárbara and Biscoito da Ferraria). The goal was to i) test if recently reforested areas will increase significantly the functional connectivity among the two reserves, when compared against the absence of such reforestations; and ii) assess if the resulting connectivity of these recent reforestations outperform randomly displaced reforested areas.

Our results showed that recent reforestations can enhance the functional connectivity between Serra de St. Bárbara and Biscoito da Ferraria. Nevertheless, this reforestation scenario showed no higher and in some cases lower improvement in functional connectivity than random reforestations. The random reforestations that presented the higher increment in individuals successful dispersion are displayed in a 'stepping-stones' format.

We showed that conservation actions should be faced against each other, as a way to ensure that the best measure is implemented.

Keywords: Agent-based model; Functional connectivity; Corridor design; Decision-making

3.2 Introduction

In a world where land-use is highly impacted by anthropogenic activities, pristine and protected native habitats are increasingly becoming more isolated, resulting in an increasingly disruption of the functional connectivity among such areas (e.g. DeFries *et al*., 2005; Joppa *et al*., 2008). Functional connectivity is perceived as the extent to which a given individual species of interest is able to move through a landscape, and its disruption can compromise gene flow, population viability, and species diversity between habitat patches, even if such patches are protected (Crooks & Sanjayan, 2006). Hence, the importance of maintaining connectivity has been recognized for several decades (Noss, 1983). This is even more important, when considering that with recent anthropogenic induced climate change, species need to shift their distribution following climatic suitability (Chen *et al*., 2011). If 'source' habitats are isolated and are no longer suitable for a given species, migration may not be possible and species survival is compromised. Thus, maintaining/increasing functional connectivity is also an answer to face global changes (Heller & Zavaleta, 2009). Functional connectivity can be increased by the construction of ecological corridors that have similar vegetation as the species' habitats (Eycott *et al*., 2012). However, the creation of ecological corridors can be complex and resource consuming (Bottrill *et al*., 2008).

The uncertainty involved regarding the real effectiveness of such measures makes their selection and implementation extremely challenging. In fact, there seems to be a lack of information to guide management actions from decision makers (Shoo *et al*., 2013). Furthermore, despite the multiple efforts for preserving biodiversity and restoring natural habitats, there are few studies that have assessed the effectiveness of implemented actions (Sutherland *et al*., 2004; Fazey *et al*., 2005). It is therefore crucial to develop methodologies and tools to support decision-making that can help to test the effectiveness of reforestation efforts and to identify the locations where those efforts should be focused in order to maximize functional connectivity. Here we apply a recently developed Agent-based model (ABM) (Aparício *et al*., in prep.b) to evaluate the effectiveness of recent reforested sites in Terceira Island, Azores, regarding their impact over local functional connectivity for ground insects. We further test the effect of several random reforestation scenarios.

3.3 Materials and Methods

Azorean archipelago is located in the North Atlantic (37° to 40° N latitude and 25° to 31° W longitude) and is composed by nine Islands. The present study focuses on Terceira Island (approximately 402 km^2), on a small area that has been recently reforested between two 'natural' patches - Serra de St. Bárbara and Biscoito da Ferraria. These two nature reserves are considered to be highly important for endemic arthropods biodiversity (Borges *et al*., 2000). Recent reforestation efforts comprised a total area of 10 hectares divided in four fragments.

In order to evaluate and quantify functional connectivity of these newly reforested areas, we applied a recently developed Agent-based model (Aparício *et al*., in prep.b). This model simulates individual movement conditioned by land-use permeability and slope, aiming to identify key areas for functional connectivity. We simulate the movement of five ground-dwelling Azorean insect species: *Alestrus dolosus*, *Aphrodes hamiltoni*, *Cedrorum azoricus azoricus*, *Drouetius borgesi borgesi* and *Trechus terrabravensis*. All these species are endemic and are highly dependent on native vegetation,

although with some differences among them in distribution, dispersal ability, and other biological and ecological traits (Borges & Serrano, 1993; Quartau & Borges, 2003; Borges *et al*., 2004; Nardi & Mico, 2010). One expert defined land-use permeability and slope thresholds, using the same settings as those in Aparício *et al*. (in prep.b). Because it was shown that no significant difference emerged from the use of different, yet realistic, mortality levels within the model, we used the intermediate mortality level (Aparício *et al*., in prep.b).

To evaluate the effect that reforested areas can have over the functional connectivity between the two natural reserves, we ran the model with three land-use sets: 'Pre-reforestation' landscape (DROTRH, 2008), 'Post-reforestation' landscape and 'Random reforestation' landscape. The 'Post-reforestation' landscape was obtained by correcting the 'Pre-reforestation' dataset to incorporate the recent reforested areas delimited through GPS (IMPACTBIO, 2016). The ´Random reforestation' landscapes were generated in NetLogo environment (Wilensky, 1999) by using as base the 'Pre-reforestation' landscape, and reforesting 10 hectares randomly between the two native areas considered. Firstly, in order to capture the pattern of effects over functional connectivity that random reforestations have, we ran a total of 200 'Random reforestation' landscapes per species. Each random landscape ran one time, generating 135 thousand individuals per landscape. This was then compared against the performance of 'Pre-reforestation' landscape and 'Post-reforestation' landscape.

Later, in order to evaluate in more detail the effect of 'Random reforestation' landscapes over functional connectivity, and compare them, we generated, saved and tested a total of 10 'Random reforestation' landscapes. In this step we ran 12 land-use sets: One 'Pre-reforestation' landscape, one 'Post-reforestation' landscape and 10 'Random reforestation' landscapes. Figure 3.1 shows the study area, with the 'Post-reforestation' landscape and one of the ten saved 'Random reforestation' landscapes. The 12 landscapes studied in detail can be seen in Figure 6.17.

In all simulations the number of individuals generated was the same. Apart from the 200 'Random reforestation', all simulations were repeated 10 times. A total of 135 thousand individuals were simulated per repetition. For further details and ODD protocol see Supplementary materials (in Section 6.1.2.2). ANOVA and Tukey pairwise test (with 95% of confidence) between connectivity outputs from reforestation scenarios were assessed. Statistical tests and data analyses were carried out in R software (R Core Team, 2015).

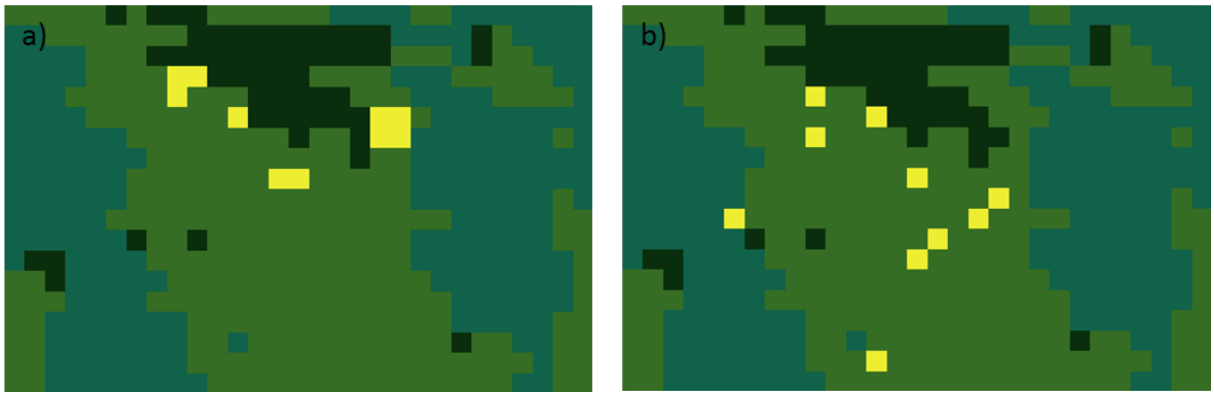

Figure 3.1 - Representation of the window of study. Dark green-blue color indicates native vegetation areas (on the left Serra de St. Bárbara and on the right Biscoito da Ferraria). Yellow areas represent reforestations, either real recent ones – post-reforestation landscape (a), or randomly generated reforestations – random landscape (b). Semi-natural grassland (green) and exotic forest plantaction (dark green) are also represented in the figure.

3.4 Results

The amount of individuals that successfully reach a different native site in the random reforestation landscapes was found to be highly dependent on the species considered: *Alestrus dolosus* presented more dispersals while *Trechus terrabravensis* presented the less number of dispersals. The number of dispersals was also found to be highly dependent from the reforestation scenario considered (p-value < 0.05). Recent reforesting efforts ('Post-reforesting' landscape) were found to increase the number of agents exchanged between Serra de St. Bárbara and Biscoito da Ferraria (Figure 6.16). *Alestrus dolosus* presented the higher increase in the average of dispersion capacity (from 62.2 to 117.5) while *Trechus terrabravensis* presented the lowest increase (from 4.3 to 13). *Aphrodes hamiltoni, Cedrorum azoricus azoricus* and *Drouetius borgesi borgesi* presented an intermediate increase on functional connectivity (from 24.1 to 48.4, from 21.5 to 39.2 and from 22.7 to 38.9, respectively). Differences among 'Pre-reforestation' landscape and 'Post-reforestation' landscape and between 'Random reforestation' landscape and 'Pre-reforestation' landscape were found to be statistically significant (p-value ≤ 0.01). Such result indicate that any reforestation effort (of 10 hectares), independently of where placed, would lead to a significant increase on functional connectivity (Figure 6.16). On the other hand, 'Random reforestation' landscape and 'Post-reforestation' landscape were not statistically different (p-value > 0.05; See Table 6.7).

When generating and comparing, in a detailed way, 10 random reforestation landscapes between Serra de St. Bárbara and Biscoito da Ferraria (i.e. 'Random reforestation' landscape) against the 'Post-reforestation' landscape, the same pattern is observed than in the previous case. Moreover, the 'Post-reforestation' landscape here inclusively, showed in some cases, a lower improvement in functional connectivity than 'Random reforestation' landscape. More precisely, 'Random reforestation No. 7' and 'Random reforestation No. 4' provided the highest increases in functional connectivity between the two areas for all the five species (Figure 3.2). Both of these random reforestation landscapes form a 'stepping-stone' type landscape, with small but close fragments. 'Random reforestation No.7' was found to be statistically different from 'Post-reforestation' landscape (p-value < 0.05), while 'Random reforestation No.4' was found to be marginally significant (p-value < 0.1; See Table 6.8). 'Random reforestation No. 7' landscape is represented in Figure 3.1b.

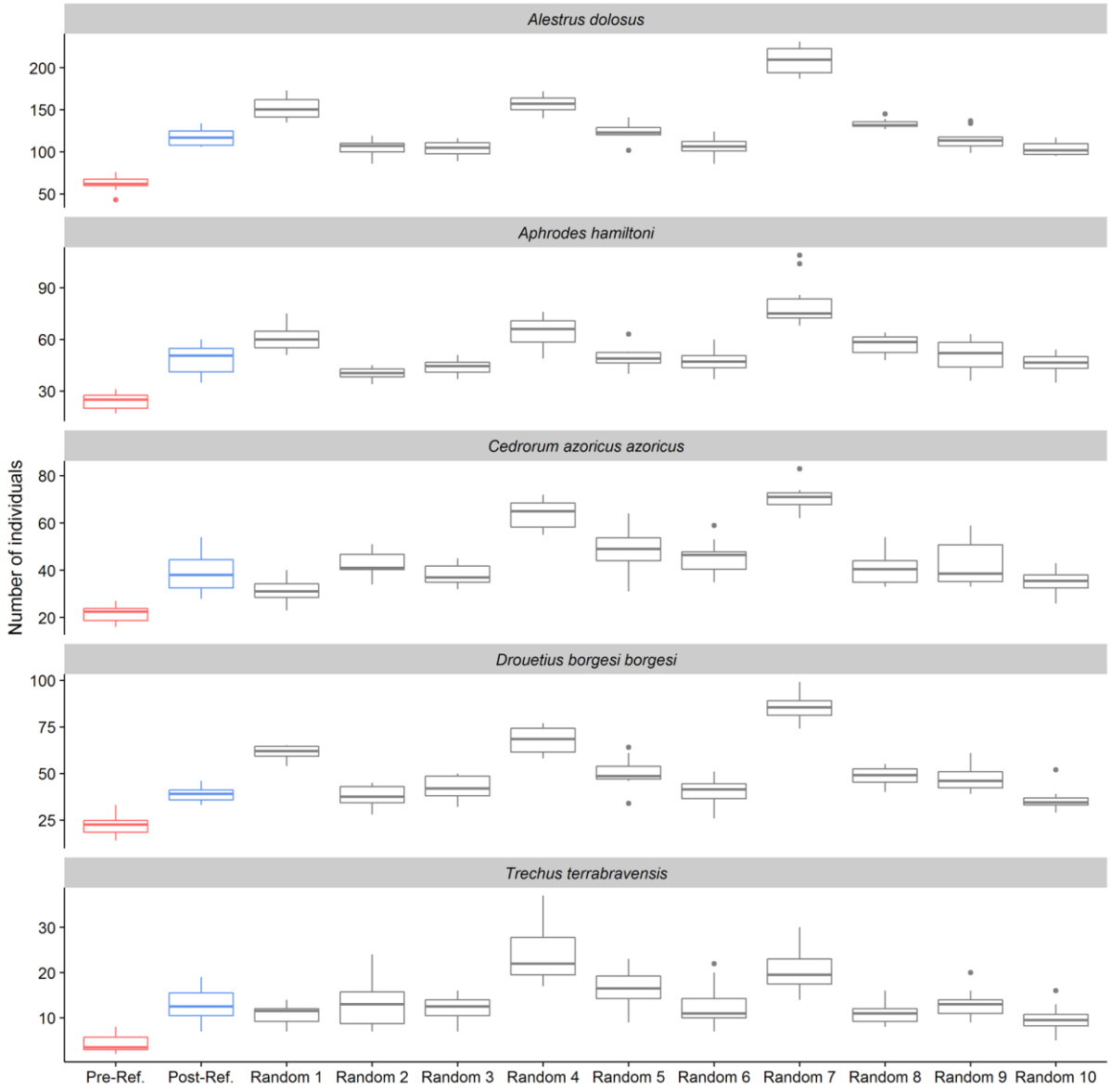

Figure 3.2 - Quantification of functional connectivity provided by different landscapes per species. 'Pre-Ref.' landscape is referent to 'Pre-reforestation' landscape (in red); 'Post-Ref.' landscape is referent to 'Post-reforestation' landscape (in blue); 'Random' landscape is referent to 'Random reforestation' landscape (with 10 difference scenarios - in grey). Dots represent outliers.

3.5 Discussion

Recent reforestations are a clear good signal from the environmental policy in Azores. These restored native sites between Serra de Santa Bárbara and Biscoito da Ferraria proved to have the potential to increase functional connectivity. For all species, our model showed that the functional connectivity increases when the scenario of 'Post-reforestation' is considered and compared with 'Pre-

reforestation' landscape. Nevertheless, any action of reforestation in the area considered, even if randomly generated, represents an increase in the success of dispersals.

Therefore, our study showed that 'Post-reforestation' landscape is no better and in some cases it is worse than randomly generated reforestations. This seems to be particularly evident when comparing the performance of 'Post-reforestation' landscape against 'Random reforestation No. 4' or 'Random reforestation No. 7' landscapes. This result can be explained by the format of 'stepping-stones' that these random landscapes present. Because such landscape present a lower distance between native matrix sites, the time spent in non-native habitats and therefore, exposed to high mortality (e.g. predation) is considerably reduced, ultimately leading to an increase in species survival (Niebuhr *et al*., 2015). Moreover, Saura *et al*. (2014) showed that stepping-stones can enhance species' movement and are crucial for species' dispersion. Hence, they can not only reduce the isolation of habitats, but also provide an opportunity for species to migrate to new suitable areas, which is particularly crucial in a scenario of climate change, where species need to move together with their climatic niche. Notwithstanding, however providing a suboptimal increment in functional connectivity, the 'Post-reforestation' landscape provides a higher amount of habitat (four larger reforested sites vs ten smaller reforested sites in 'Random reforestation No. 7'), which is thought to increase the population size (Niebuhr *et al*., 2015) and consequently the genetic variation of the population (Frankham, 1996). Moreover, the edge effect over species can be reduced when compared with a 'stepping-stone' landscape type, since the distance between the edge of the native habitat and its interior is larger. This appears to be especially important for specialist species, which are known to have stronger responses to edge effect (Peyras *et al*., 2013). Hence, we speculate that such sites could act as important refugia sites in context of climate change.

Our results indicate that conservation measures, such as the reforestations implemented in Terceira Island, should be tested before implemented, and their performance should be compared, in order to maximize the benefits of the investment. The approach used here can easily be applied to test and illustrate the effects of different management options for a variety of habitats and species and could contribute to support decision-making and, ultimately, achieve a better long-term conservation management (Redpath *et al*., 2013). As anticipated in Aparício et al. (in prep.b), this study reinforces our belief that ABMs can play an important role in landscape management and species conservation.

3.6 Acknowledgements

We would like to thank the anonymous reviewers that helped improve the quality of this manuscript.
A special thanks to David Avelar, for facilitating the computational resources. This project was partially financed by FCT Unit funding (Ref. UID/BIA/00329/2013).

Chapter 4 - General discussion

4.1 Thesis contributions to science

We proved this model to be the technique that produces more reliable connectivity maps when compared with three of the most used methodologies that are used to assess species' movement through landscapes. The fact that it can easily incorporate other parameters (that can affect species' connectivity) and therefore increase its complexity, can make our model easily applied to other species, in different landscapes.

Our study included five ground dwelling endemic species from Azores, and allowed a much more detailed spatial analysis of the current landscape implications to species survival, taking into consideration climate change. Given the biodiversity richness in the Azorean archipelago, and specifically of arthropods (Borges *et al*., 2010), we acknowledge that our five species may not contemplate the diversity presented in the island. Rather, our species are regarded as sentinel species, and this study as a warning signal. Furthermore, we believe that our study represents an important and direct contribution to environmental management and species conservation, as its' results are a direct contribution to the Regional Plan of Adaptation to Climate Change in Azores project (PRAC). In summary, this study allowed for a spatial identification of the most important areas to maintain and restore, in order to enhance the dispersion and, ultimately, contribute to the preservation of the five studied species in a scenario of climate change. We believe that, considering the diversity of the species chosen and the consistency in results between them, those areas will also favor many other species.

Our model was able to generate and compare different scenarios of conservation efforts. Therefore, different areas hypothesized for the implementation of new management measures that would improve functional connectivity can be compared. This allows to take into consideration relative connectivity values, as well as to generate discussions between scientists, decision-makers and stakeholders. Because this work was done as part of PRAC project, we expect that the results here presented will be taken into account when new conservation actions are to be designed and implemented.

In a more general sense, it is our belief that this method can be used to address some of the identified barriers that are currently undermining conservation management, namely: i) lack of communication and information flow between scientists and stakeholders (Koschke *et al*., 2014); ii) little guidelines regarding management actions provided to the decision-makers (Shoo *et al*., 2013), and iii) lack of knowledge on the impact of alternative measures (Redpath *et al*., 2013). Ultimately, if all these barriers are handled correctly, we anticipate that our model can improve the probability of achieving a more effective long-term conservation management (Redpath *et al*., 2013).

4.2 Conservation efforts

Humans have been altering the composition of biological communities for a long time and in several ways, leading many species to extinction (Vitousek *et al*., 1997). Besides the ethical and aesthetical reasons, the change in local species (both in presence and abundance) has the potential to disturb ecosystems proprieties (Zimov *et al*., 1995). Moreover, it seems that proprieties of ecosystems are

highly dependent on biodiversity: either on the functional characteristics of the biota present in a given local, or on the abundance and distribution of such organisms over space and time (Hooper *et al*., 2005). Costanza *et al*., (1997) valued the global ecosystem services at US$33 trillion per year (with invertebrates having a significant importance to this amount); each year that passes, 50 billion Euros are lost in worth due to biodiversity loss. Such amount of growth could have been produced as Ecosystem Services (Braat & ten Brink, 2008). These losses are projected to increase and by 2050 the biodiversity loss is projected to represent 7% of the current World's GDP (Braat & ten Brink, 2008).

Management actions seem to be urgent in order to preserve biodiversity. One of these management actions that have been proposed is the construction of ecological corridors, which would increase the movement among patches of habitats, reducing the risk of extinction (Lande, 1993), and allowing species to follow climatic suitability (McGuire *et al*., 2016), and therefore counteracting the effects of climate change and habitat destruction and fragmentation.

To better develop effective landscape conservation initiatives, the understanding of animal movement and ecological processes that depend on connectivity seem to be essential. Generally, these require the quantification of how connectivity is affected by landscape structure (McRae *et al*., 2008; Zeller *et al*., 2012). It is our belief that any effort to increase functional connectivity in Azores should be done recurring to native vegetation structurally similar from the matrixes found within the reserves, but also typical vegetation of the altitude where interventions are required should be considered (see Elias *et al*., 2016). This, would not only increase species movement to their full potential (Prevedello & Vieira, 2010; Eycott *et al*., 2012), but also is expected to increase the amount of native and endemic species over invasive and exotic species (Borges *et al*., 2006; Florencio *et al*., 2013). Moreover, these reforestations do not seem to be particularly expensive or time-consuming, since whenever the grazing intensity decreases, the semi-natural pastures are easily invaded by the shrub *Erica azorica*, the initial plant appearing in the succession towards Laurisilva forest (Elias & Dias, 2009).

As referred in chapter 3 – "Implications of recent reforestations in Terceira Island (Azores) for functional connectivity – An application of a new Agent-based model" - recently, some reforestations took place between Serra de St. Bárbara and Biscoito da Ferraria. We were able to show that an increase in functional connectivity can be expected between the two native reserves due to these reforestation efforts. Notwithstanding, if the true objective of such reforestations was to improve functional connectivity, this landscape is unable to maximize functional connectivity, as it was shown to perform equally and sometimes worse than randomly generated reforestations (with the same amount of hectares converted). Furthermore, our findings suggest that a 'stepping-stone' type landscape maximizes the functional connectivity between native areas, as previously reported by some authors (Saura *et al.*, 2014). It is however important to bear in mind that the size and location of such 'stepping-stones' need to be appropriate for the species, or otherwise, the dispersion movement could be disrupted (Kramer-Schadt *et al*., 2011). It is therefore useful that these solutions are tested for their effective benefits for connectivity using tools such as the method developed and presented in this thesis.

Changes in land-use that try to accomplish biodiversity goals usually are not easily implemented, as they typically impact negatively the economy and social systems (e.g. Jenkins *et al*., 2015). Taking the recent reforested sites as an example, by planting native vegetation where was once semi-natural grasslands or exotic forests, the incoming generated from cattle breeding and timber was reduced. By exposing this simple example, we recognize that land-use changes have the potential to be highly problematic when all the different stakeholders' opinions are not considered. For instance, Knight *et al*., (2011) found that only a small part of the land managers that possess their land inside a

planning region were willing-to-sell their land. Such barriers can undermine any attempt to meet the conservation goals. Hence, public participation appears to be necessary for a successful environmental policy (Eden, 1996), and in the particular case of corridor design, it seems to be indispensable for the population to understand the concept of ecological corridors (Brown & Harris, 2005).

The application of our model possesses the advantage to produce visual maps that decision-makers can easily understand (Theobald *et al*., 2000). Moreover, we were also able to test and compare different scenarios of conservation regarding the effect that reforestation can have over functional connectivity. We were able to show that recent reforestations provide only a suboptimal increase in functional connectivity, and are easily outperformed by random reforestations that form a 'stepping-stone' alike landscape. Such result emphasizes the need to compare different scenarios of conservation, before implementing one. In this context, it is our expectation that our model can also be used to generate discussion among stakeholders and help to a better understanding on conservation actions from the local population, as people *'... will not support what they do not understand and cannot understand that in which they are not involved*' (FEMAT, 1993).

4.3 Study limitations

There are some limitations that are expected in any modeling effort such as ours. The lack of empirical data regarding species movement forced us to recur to an expert opinion regarding it. Thus, the choice of our set of species was limited to the range of expertise available. Moreover, such subjective evaluation of species usually results in sub-optimal parameterization, when compared to empirical data (Clevenger *et al*., 2002). Also, in our model we did not considered differences among sites within the same land-use area (e.g. habitats mapping). Characteristics like microclimate and microhabitats (Roslin *et al*., 2009), habitat quality or vegetation size (Avendaño-Mendoza *et al*., 2005), or even soil hardness (Arellano *et al*., 2008) are known to influence insects movement preferences. Moreover, we acknowledge that we did not fully take advantage of our ABM. For instance, variability among individuals (e.g. colonization capacity or dispersion ability; see e.g. Otronen & Hanski, 1983) and species interactions (Araújo & Luoto, 2007), that are known to influence species dynamics, were not included in the models. This is easily understandable by the huge amount of data that would be required to include such parameters in a model. Also, in no part of our study we considered that species can have adaptive capacity (e.g. Nussey *et al*., 2005), or that species possess phenotypic plasticity that allows them to persist in the new climate (Root *et al*., 2003; Sheridan & Bickford, 2011). Although unlikely, if these are ongoing adaptive processes in Azorean insects, migration may cease to be a necessity.

Because we did not use climate data directly, our model was dependent on previously SDMs. Since SDMs was proven to vary with the type of data used (Duputié *et al*., 2014) and between emission scenarios (Porfirio *et al*., 2014), our results need to be interpreted with warning, as they were built only on the most extreme scenario, i.e. RCP 8.5. Nonetheless, we consider that the results obtain are relevant to understand the potential effects of climate change on connectivity. Thus, in milder scenarios, we expect to find a reduction in usable area, even if to a lower extent.

Any computational simulation is highly dependent on computational resources. In order to avoid a profound increase the computational time required for the simulations, we choose not to include more species to our set. For the same reason, we chose to lower the cells' resolution to 100 meters, which can also influence the outcomes of simulations (McRae *et al*., 2008).

4.4 Future studies

The model that we here developed and presented can be considered the basis for future landscape and corridor design research. Because the ABM was developed under the scope of the present master's thesis and is new to the scientific community, we acknowledge that much is yet to be done. For instance, the complexity of the model may increase (e.g. introduce interactions among individuals, maximum dispersion, reproduction, etc.). Nonetheless, any increase in parameterization depends greatly on data available for the simulated species, which can be highly challenging to obtain.

If more studies are to be conducted in Terceira Island, we recommend testing the impact in functional connectivity between Serra de St. Bárbara, Biscoito da Ferraria and Matela since we identified this to be one of the most priority sites for increasing overall connectivity for the five studied species. A comparison between the increment in connectivity as a result of the recent reforestations and the increment that we expect if this priority area was to be reforested (in the same amount of hectares) can be easily assessed using our model. It is our hope that this study will allow to corroborate that this area is efficient in improving connectivity. Regarding empirical data of species movement, because our species are rare and difficult to capture, we recommend studying insects' movement across different habitat matrixes in a 'microlandscape' scale (see Wiens & Milne, 1989). Such approach allows a better characterization of species movement patterns, by ranking the different land-uses regarding species preference of use.

Further studies can use the model here presented to develop connectivity or corridors design studies in different contexts from the ones presented here. One easy way to do this is by apply the model to species with higher dispersal capacity, and in a continental landscape. Other interesting study that can test our model is by, instead of randomly assessing individuals in the landscape, the 'source' of focal species would be real populations in the landscape. This exercise would require information regarding species real distribution, which requires a great knowledge on species. Following this idea, the model can also be applied for a more detailed study of the functional connectivity among several populations. The resulting paths could then be compared with the other algorithms here presented (Circuit-theory, Least-cost Path and Dispersal paths).

Moreover, the model fed only on expert knowledge based-matrix. We assume that a good strategy to evaluate our model and the data analysis that we proceeded is to base the resistance matrix on empirical data of movement patterns, and then compare the connectivity map to known patterns of occupancy (i.e. pitfall data). We would expect the fit to be higher in such case than the results here presented.

Since the results of our model are highly dependent of SDMs, one could apply our model with SDMs produced under different RCPs scenarios. This approach would allow to evaluate and quantify the impacts that different scenarios of climate change can have over functional connectivity. Furthermore, this could also be added to the calculus of the priority areas for restoration, being the areas that are coincident among the simulations with different SDMs considered with higher priority.

Finally, because our model can easily incorporate and generate different conservation scenarios, we anticipate that it can be tested in a stakeholder workshop context, allowing, for example, to rapidly testing the effectiveness of different proposed solutions. Ultimately, this approach would allow to ensure that the best conservation strategy possible is achieved.

4.5 Final remarks

With the present study we were able to show that SDMs should take into consideration the landscape design. If we apply our connectivity model results to the SDMs that had been previously conducted to assess the potential impacts of climate change on Terceira insects, we easily understand that the amount of area used for species movement is far lower than suitable area projected by climatic variables. In another words, if land-use is not considered, scientists may underestimate the real threats to biodiversity that arise from climate change, ultimately undermining any conservation efforts.

Our study supports ABMs as a powerful and promising tool to study landscape ecology, and more precisely functional connectivity. We confirm that ABMs are capable of easily explain more empirical data than the most used algorithms for such studies. Equally, we also confirm ABMs as a flexible tool that allows a wide range of diverse important studies that can influence and support decision-makers. We set our model as the basis of more connectivity studies, but more complexity can be easily implemented (as long as data is available), which would further reduce the uncertainty related with the simulations. This would allow for much more detailed studies on species and/or populations.

Regarding the results of our simulations in Terceira Island, we revealed that apart from the areas near Biscoito da Ferraria, all other native vegetation sites are fairly disconnected for all species. Without surprise, the same sites near Biscoito da Ferraria were identified as the ones that allow a higher movement from species, i.e. formed more corridors, and were therefore identified as the most important to restore. The restoration in these areas would enhance functional connectivity for current and future climatic conditions for all (under current climatic conditions) and almost all (four in five, under future climatic conditions) of the studied species, respectively. Other areas that were also highlighted as important to restore are located between Serra de St. Bárbara, Biscoito da Ferraria and Matela. These sites were identified as priority for three out of the five species, being the exceptions *Cedrorum azoricus azoricus* and *Trechus terrabravensis*, the most restrict species regarding habitat preferences. Interventions in such areas could benefit a high amount of species, since both Serra de St. Bárbara and Biscoito da Ferraria are known to be extremely rich in arthropods biodiversity. *Cedrorum azoricus azoricus* and *Trechus terrabravensis* are projected to be highly vulnerable to climate change, and localized and precise management actions should be hypothesized in order to enhance species persistence.

Regarding the reforestation effort that has been done in the recent years between Serra de St. Bárbara and Biscoito da Ferraria, our study showed that an increase in functional connectivity can be expected. However, if the true objective of such reforestations was to improve functional connectivity, this landscape is unable to maximize functional connectivity, as it was shown to perform equally and sometimes worse than randomly generated reforestations. Furthermore, we found that a 'stepping-stone' type landscape can maximize the functional connectivity between two native areas. If current reforestations are to be continued, we recommend reforestation effort to be extended a little south, so that the connectivity around the Matela area is enhanced, as it comprises also one of the areas identified as priority for restoration (as cited above). Nevertheless, we should acknowledge that the recent restoration is a clear good signal that environmental changes may be promoted in a short-term, as some actions are already underway.

We expect that our study can have a positive and significant impact for designing and planning new corridor areas. We must however, alert that any plan for modifications in the land-use should promote and acknowledge public consultation as a tool for planning improvement and problem

solving. Furthermore, such empowerment actions are essential to ensure the success of environmental policies.

Chapter 5 - Bibliography

Adriaensen, F., Chardon, J.P., de Blust, G., Swinnen, E., Villalba, S., Gulinck, H. & Matthysen, E. (2003) The application of least-cost' modelling as a functional landscape model. *Landscape and urban planning*, **64**, 233-247.

Allen, C.H., Parrott, L. & Kyle, C. (2016) An individual-based modelling approach to estimate landscape connectivity for bighorn sheep (*Ovis canadensis*). *PeerJ*, 4:e2001.

Andreassen, H.P., Halle, S. & Ims, R.A. (1996) Optimal width of movement corridors for root voles: not too narrow and not too wide. *Journal of Applied Ecology*, **33**, 63–70.

Andersen, K.K. , Azuma, N., Barnola, J.M., Bigler, M., Biscaye, P., Caillon, N., Chappellaz, J., Clausen, H.B., Dahl-Jensen, D., Fischer, H., Flückiger, J., Fritzsche, D., Fujii, Y., Goto-Azuma, K., Grønvold, K., Gundestrup, N.S., Hansson, M., Huber, C., Hvidberg, C.S., Johnsen, S.J., Jonsell, U., Jouzel, J., Kipfstuhl, S., Landais, A., Leuenberger, M., Lorrain, R., Masson-Delmotte, V., Miller, H., Motoyama, H., Narita, H., Popp, T., Rasmussen, S.O., Raynaud, D., Röthlisberger, R., Ruth, U., Samyn, D., Schwander, J., Shoji, H., Siggard-Andersen, M.L., Steffensen, J.P., Stocker, T. , Sveinbjörnsdottir, A.E., Svensson, A., Takata, M., Tison, J.L., Thorsteinsson, T., Watanabe, O., Wilhelms, F. & White, J. (2004) High-resolution record of the Northern Hemisphere climate extending into the last interglacial period. *Nature*, **431**, 147-151.

Aparício, B.A., Ascensão, F., Cascalho, J., Borges, P.A.V. & Cruz, M.J. (in prep.a) Implications of recent reforestations in Terceira Island (Azores) for functional connectivity – An application of a new Agent-based model.

Aparício, B.A., Cascalho, J., Cruz, M.J., Borges, P.A.V. & Ascensão, F. (in prep.b) Climate Change implications on landscape functional connectivity: a case study with insects in Terceira Island.

Araújo, M.B., Alagador, D., Cabeza, M., Nogués-Bravo, D. & Thuiller, W. (2011) Climate change threatens European conservation areas. *Ecology Letters*, **14**, 484–492.

Araújo, M.B. & Luoto, M. (2007) The importance of biotic interactions for modelling species distributions under climate change. *Global Ecology and Biogeography*, **16**, 743–753.

Arechavaleta, M., Rodríguez, S., Zurita, N. & García, A. (2010) *Lista de especies silvestres de Canarias. Hongos, plantas y animales terrestres 2009*. Gobierno de Canarias, Spain.

Arellano, L., León-Cortés, J.L. & Ovaskainen, O. (2008) Patterns of abundance and movement in relation to landscape structure: a study of a common scarab (*Canthon cyanellus cyanellus*) in Southern Mexico. *Landscape Ecology*, **23**, 69–78.

Arifin, S.N., Zhou, Y., Davis, G.J., Gentile, J.E., Madey, G.R. & Collins, F.H. (2014) An agent-based model of the population dynamics of *Anopheles gambiae*. *Malaria journal*, **13**, 1-19.

Ascensão, F., Grilo, C., LaPoint, S., Tracey, J., Clevenger, A.P. & Santos-Reis, M. (2014). Inter-individual variability of Stone Marten behavioral responses to a highway. *Public Library of Science one*, **9**, e103544.

Avendaño-Mendoza, C., Morón-Ríos, A., Cano, E.B. & León-Cortés, J. (2005) Dung beetle community (Coleoptera: Scarabaeidae: Scarabaeinae) in a tropical landscape at the Lachua region, Guatemala. *Biodiversity Conservation*, **14**, 801–822.

Axelrod, R. (1997) *The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration*. Princeton University Press, Princeton, USA.

Barbet-Massin, M., Thuiller, W. & Jiguet, F. (2012) The fate of European breeding birds under climate, land-use and dispersal scenarios. *Global Change Biology*, **18**, 881–890.

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental,T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Mersey, B. & Ferrer, E.A. (2011) Has the Earth's sixth mass extinction already arrived? *Nature*, **471**, 51–57.

Barton, K.A., Phillips, B.L., Morales, J.M. & Travis, J.M.J. (2009) The evolution of an 'intelligent' dispersal strategy: biased, correlated random walks in patchy landscapes. *Oikos*, **118**, 309-319.

Beier, P., Spencer, W.D., Baldwin, R.F. & McRae, B.H. (2011) Towards best practices for developing regional connectivity maps. *Conservation Biology*, **25**, 879–892.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W. & Courchamp, F. (2012) Impacts of climate change on the future of biodiversity. *Ecology letters*, **15**, 365-377.

Bocedi, G., Palmer, S.C.F., Pe'er, G., Heikkinen, R.K., Matsinos, Y.G., Watts, K. & Travis J.M.J. (2014) RangeShifter: a platform for modelling spatial eco-evolutionary dynamics and species' responses to environmental changes. *Methods in Ecology and Evolution*, **5**, 388–396.

Bodin, Ö. & Saura, S. (2010). Ranking individual habitat patches as connectivity providers: Integrating network analysis and patch removal experiments. *Ecological Modelling*, **221**, 2393–2405.

Borges, P.A.V., Aguiar, C., Amaral, J., Amorim, I.R., André, G., Arraiol, A.,. Baz A., Dinis, F., Enghoff, H., Gaspar, C., Ilharco, F., Mahnert, V., Melo, C., Pereira, F., Quartau, J.A., Ribeiro, S., Ribes, J., Serrano, A.R.M., Sousa, A.B., Strassen, R.Z., Vieira, L., Vieira, V., Vitorino, A. & Wunderlich, J. (2005). Ranking protected areas in the Azores using standardized sampling of soil epigean arthropods. *Biodiversity and Conservation*, **14**, 2029-2060.

Borges, P.A.V., Costa, A., Cunha, R., Gabriel, R., Gonçalves, V., Martins, A.F., Melo, I., Parente, M., Raposeiro, P., Rodrigues, P., Santos, R.S., Silva, L., Vieira, P. & Vieira, V. (2010) *A list of the terrestrial and marine biota from the Azores*. Princípia, Cascais, Portugal.

Borges, P.A.V., Lobo, J.M., Azevedo, E.B., Gaspar, C., Melo, C. & Nunes, V.L. (2006) Invasibility and species richness of island endemic arthropods: a general model of endemic vs. exotic species. *Journal of Biogeography*, **33**, 169–187.

Borges, P.A.V. & Serrano, A.R.M. (1993) New taxa of Poecilini (Coleoptera, Carabidae, Pterostichinae) from Azores. *Bollettino del Museo Regionale di Scienze Naturali - Torino*, **11**, 315-329.

Borges, P.A.V., Serrano, A.R.M. & Amorim, I.R. (2004) New species of cave-dwelling beetles (Coleoptera: carabidae: trechinae) from the Azores. *Journal of natural history*, **38**, 1303–1313.

Borges, P.A.V., Serrano, A.R. & Quartau, J.A. (2000) Ranking the Azorean Natural Forest Reserves for conservation using their endemic arthropods. *Journal of Insect Conservation*, **4**, 129–147.

Bottrill, M.C., Joseph, L.N., Carwardine, J., Bode, M., Cook, C., Game, E.T., Grantham, H., Kark, S., Linke, S., McDonald-Madden, E., Pressey, R.L., Walker, S., Wilson, K.A. & Possingham H.P. (2008) Is conservation triage just smart decision making? *Trends in Ecology & Evolution*, **23**, 649–654.

Braat, L. & ten Brink, P. (2008) *The cost of policy inaction: the case of not meeting the 2010 biodiversity target.* Study/Report for the European Commission, DG Environment, Wageningen, Netherland.

Bradshaw, A. (1991) The Croonian Lecture, 1991: Genostasis and the Limits to Evolution. *Philosophical Transactions: Biological Sciences*, **333**, 289-305.

Brambilla, M. & Ficetola, G.F. (2012) Species distribution models as a tool to estimate reproductive parameters: a case study with a passerine bird species. *Journal of Animal Ecology*, **81**, 781–787.

Brown, R. & Harris, G. (2005) Comanagement of wildlife corridors: the case for citizen participation in the Algonquin to Adirondack proposal. *Journal of Environmental Management*, **74**, 97–106.

Cardoso, P., Aranda, S.C., Lobo, J.M., Dinis, F., Gaspar, C. & Borges, P.A.V. (2009) A spatial scale assessment of habitat effects on arthropod communities of an oceanic island. *Acta Oecologica*, **35**, 590-597.

Cardoso, P., Arnedo, M.A., Triantis, K.A. & Borges, P.A.V. (2010) Drivers of diversity in Macaronesian spiders and the role of species extinction. *Journal of Biogeography*, **37**, 1034-1046.

Cardoso, P., Erwin, T.L., Borges, P.A.V. & New, T.R. (2011) The seven impediments in invertebrate conservation and how to overcome them. *Biological Conservation*, **144**, 2647–2655.

Cardoso, P., Rigal, F., Fattorini, S., Terzopoulou, S. & Borges, P.A.V. (2013) Integrating landscape disturbance and indicator species in conservation studies. *Public Library of Science one*, **8**, e63294.

Carine, M.A. & Schaefer, H. (2010) The Azores diversity enigma: why are there so few Azorean endemic flowering plants and why are they so widespread? *Journal of Biogeography*, **37**, 77-89.

Chen, I.C., Hill, J.K., Ohlemüller, R., Roy, D.B. & Thomas, C.D. (2011) Rapid Range Shifts of Species Associated with High Levels of Climate Warming. *Science*, **333**, 1024-1026.

Christie, M.R. & Knowles, L.L. (2015) Habitat corridors facilitate genetic resilience irrespective of species dispersal abilities or population sizes. *Evolutionary Applications*, **8**, 454–463.

Clevenger, A.P., Wierzchowski, J., Chruszcz, B. & Gunson, K. (2002) GIS-Generated, Expert-Based Models for Identifying Wildlife Habitat Linkages and Planning Mitigation Passages. *Conservation Biology*, **16**, 503–514.

Collins, E., Kearins, K. & Roper, J. (2005) The risks in relying on stakeholder engagement for the achievement of sustainability. *Electronic Journal of Radical Organisation Theory*, **9**, 81-101.

Connor, S.E., van Leeuwen, J.F.N., Rittenour, T.M., van der Knaap, W.O., Ammann, B. & Björck, S. (2012) The ecological impact of oceanic island colonization – a palaeoecological perspective from the Azores. *Journal of Biogeography*, **39**, 1007–1023

Coope, G.R. & Wilkins, A.S. (1994) The response of insect faunas to glacial-interglacial climatic fluctuations. *Philosophical Transactions: Biological Sciences*, **344**, 19-26.

Costanza, R., d'Arge, R., de Groot, R., Faber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P. & van den Belt, M. (1997) The value of the world's ecosystem services and natural capital. *Nature*, **387**, 253-260.

Coulon, A., Aben, J., Palmer, S.C.F., Stevens, M., Callens, T., Strubbe, D., Lens,I., Matthysen, E., Baguette, M. & Travis, J.M.J. (2015) A stochastic movement simulator improves estimates of landscape connectivity. *Ecology*, **96**, 2203–2213.

Courchamp, F., Hoffmann, B.D., Russell, J.C., Leclerc, C. & Bellard, C. (2014) Climate change, sea-level rise, and conservation: keeping island biodiversity afloat. *Trends in Ecology & Evolution*, **29**, 127-130.

Cox, P.M., Betts, R. A., Jones, C.D., Spall, S.A. & Totterdell, I.J. (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, **408**, 184–187.

Crooks, K.R. & Sanjayan, M.A. (2006) *Connectivity Conservation: Maintaining Connections for Nature*. Cambridge University Press, Cambridge, UK.

Crowley, T.J. (2000) Causes of Climate Change Over the Past 1000 Years. *Science*, **289**, 270-277.

Cruz, M.J., Robert, E.M.R., Costa, T., Avelar, D., Rebelo, R. & Pulquério, M. (2016) Assessing biodiversity vulnerability to climate change: testing different methodologies for Portuguese herpetofauna. *Regional Environmental Change*, **16**, 1293-1304.

Davis, M.B. & Shaw, R.G. (2001) Range shifts and adaptive responses to quaternary climate change. *Science*, **292**, 673-79.

Damschen, E.I., Brudvig, L.A., Haddad, N.M., Levey, D.J., Orrock, J.L. & Tewksbury, J.J. (2008) The movement ecology and dynamics of plant communities in fragmented landscapes. *Proceedings of the National Academy of Sciences*, **105**, 19078–19083.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C. U., Hvldberg, C.S., Steffensen, J.P., Sveinbjörnsdottir, A.E., Jouzel, J. & Bond, G. (1993) Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature*, **364**, 218-220.

DeAngelis, D.L. & Mooij, W.M. (2005) Individual-based modeling of ecological and evolutionary processes. *Annual Review of Ecology, Evolution, and Systematics*, **36**, 147-168.

de Azevedo, E.B. (2001) Condicionantes Dinâmicas do Clima do Arquipélago dos Açores - Elementos para o seu estudo. *Açoreana*, **9**, 309-317.

de Azevedo, E.B. & Reis, F.V. (2016) *Cenários climáticos para os Açores: Plano Regional das Alterações Climáticas (PRAC)*. Relatório principais resultados, Angra do Heroísmos, Azores, Portugal.

DeFries, R., Hansen, A., Newton, A. & Hansen, M. (2005) Increasing isolation of protected areas in tropical forest over the past twenty years. *Ecological Applications*, **15**, 19–26.

Doerr, V.A.J., Barrett, T. & Doerr, E.D. (2011) Connectivity, dispersal behaviour and conservation under climate change: a response to Hodgson. *Journal of Applied Ecology*, **48**, 143–147.

DROTRH (2008) *Carta de ocupação do solo da região Autónoma dos Açores - Projecto SUEMAC*. Secretaria Regional do Ambiente, Direcção Regional do Ordenamento do território e dos Recursos Hídricos, Ponta Delgada, Azores.

Duputié, A., Zimmermann, N.E. & Chuine, I. (2014) Where are the wild things? Why we need better data on species distribution. *Global Ecology and Biogeography*, **23**, 457–467.

Easterling, D.R., Meehl, J., Parmesan, C., Chagnon, S., Karl, T.R. & Mearns, L.O. (2000) Climate extremes: observations, modeling, and impacts. *Science*, **289**, 2068-74.

Eden, S. (1996) Public participation in environmental policy: considering scientific, counter-scientific and non-scientific contributions. *Public Understanding of Science*, **5**, 183-204.

EEA (2009) *Progress towards the European 2010 biodiversity target — indicator fact sheets*. EEA Technical report No 5/2009, European Environment Agency, Copenhagen, Denmark.

Elias, R.B. & Dias, E. (2009) Gap dynamics and regeneration strategies in Juniperus-Laurus forests of the Azores Islands. *Plant Ecology*, **200**, 179–189.

Elias, R.B., Gil, A., Silva, L., Fernández-Palacios, J.M., Azevedo, E.B. & Reis, F. (2016) Natural zonal vegetation of the Azores Islands: characterization and potential distribution. *Phytocoenologia*, **46**, 107–123.

Elmhagen, B., Eriksson, O. & Lindborg, R. (2015) Implications of climate and land-use change for landscape processes, biodiversity, ecosystem services, and governance. *Ambio*, **44**, 1–5.

Eycott, A.E., Stewart, G.B., Buyung-Ali, L.M., Bowler, D.E., Watts, K. & Pullin, A.S. (2012) A meta-analysis on the impact of different matrix structures on species movement rates. *Landscape Ecology*, **27**, 1263-1278.

Fazey, I., Fischer, J. & Lindenmayer, D.B. (2005) What do conservation biologists publish? *Biological conservation*, **124**, 63-73.

FEMAT - Forest Ecosystem Management Assessment Team (1993) *Forest Ecosystem Management: An ecological, economic, and social assessment*. US Government Printing Office, Washington DC, USA

Fernández-Palacios, J.M., de Nascimento, L., Otto, R., Delgado, J.D., García-del-Rey, E., Arévalo, J.R. & Whittaker, R.J. (2011) A reconstruction of Palaeo-Macaronesia, with particular reference to the long-term biogeography of the Atlantic island laurel forests. *Journal of Biogeography*, **38**, 226–246.

Ferreira, M.T., Cardoso, P., Borges, P.A.V., Gabriel, R., de Azevedo, E.B., Reis, F., Araújo, M.B. & Elias, R.B. (2016) Effects of climate change on the distribution of indigenous species in oceanic islands (Azores). *Climatic Change*, **138**, 603-615.

Fischer, J. & Lindenmayer, D.B. (2007) Landscape modification and habitat fragmentation: a synthesis. *Global Ecology and Biogeography*, **16**, 265-280.

Florencio, M., Cardoso, P., Lobo, J.M., de Azevedo, E.B. & Borges, P.A.V. (2013) Arthropod assemblage homogenization in oceanic islands: the role of indigenous and exotic species under landscape disturbance. *Diversity and Distributions*, **19**, 1450–1460.

Florencio, M., Rigal, F., Borges, P.A.V., Cardoso, P., Santos, A.M.C. & Lobo, J.M. (2016) The role of plant fidelity and land-use changes on island exotic and indigenous canopy spiders at local and regional scales. *Biological Invasions*, **18**, 2309–2324.

Frankham, R. (1996) Relationship of genetic variation to population size in wildlife. *Conservation Biology*, **10**, 1500-1508.

Françoso, R.D., Brandão, R., Nogueira, C.C., Salmona, Y.B., Machado, R.B. & Colli, G.R. (2015) Habitat loss and the effectiveness of protected areas in the Cerrado Biodiversity Hotspot. *Natureza & Conservação*, **13**, 35–40.

Füssel, H-M. & Jol, A. (2012) *Climate change, impacts and vulnerability in Europe 2012: an indicator-based report*. EEA Report No 12/2012, European Environment Agency, Copenhagen, Denmark.

Gabriel, R. & Bates, J.W. (2005) Bryophyte community composition and habitat specificity in the natural forests of Terceira, Azores. *Plant Ecology*, **177**, 125-144.

Garcia, R.A., Cabeza, M., Rahbek, C. & Araújo, M.B. (2014) Multiple dimensions of climate change and their implications for biodiversity. *Science*, **344**, 1247579.

Gaspar, C., Borges, P.A.V. & Gaston, K.J. (2008) Diversity and distribution of arthropods in native forests of the Azores archipelago. *Arquipélago - Life and Marine Sciences*, **25**, 1–30.

Gaspar, C., Gaston, K.J., Borges, P.A.V. & Cardoso, P. (2011) Selection of priority areas for arthropod conservation in the Azores archipelago. *Journal of Insect Conservation*, **15**, 671-684.

Gilbert-Norton, L., Wilson, R., Stevens, J.R. & Beard, K.H. (2010) A Meta-Analytic Review of Corridor Effectiveness. *Conservation Biology*, **24**, 660-668.

Gitay, H., Suárez, A. & Watson, R.T. (2002) *Climate change and biodiversity*. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Gregory, R.D., Willis, S.G., Jiguet, F., Voříšek, P., Klvaňová, A., van Strien, A., Huntley, B., Collingham, Y.C., Couvet, D. & Green, R.E. (2009) An Indicator of the Impact of Climatic Change on European Bird Populations. *Public Library of Science one*, **4**, e4678.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S.K., Huse, G., Huth, A., Jepsen, J.U., Jørgensen, C., Mooij, W.M., Müller, B., Pe'er, G., Piou, C., Railsback, S.F., Robbins, A.M., Robbins, M.M., Rossmanith, E., Rüger, N., Strand, E., Souissi, S., Stillman, R.A., Vabø, R., Visser, U. & DeAngelis, D.L. (2006) A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, **198**, 115 – 126.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J. & Railsback, S.F. (2010) The ODD protocol: a review and first update. *Ecological Modelling*, **221**, 2760 – 2768.

Haddad, N.M., Bowne, D.R., Cunningham, A., Danielson, B.J., Levey, D.J., Sargent, S. & Spira, T. (2003) Corridor use by diverse taxa. *Ecology*, **84**, 609–615.

Haddad, N.M., Brudvig, L.A., Damschen, E.I., Evans, D.M., Johnson, B.L., Levey, D.J., Orrock, J.L., Resasco, J., Sullivan, L.L., Tewksbury, J.J., Wagner, S.A. & Weldon, A.J. (2014) Potential negative ecological effects of corridors. *Conservation Biology*, **28**, 1178–1187

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S. & Samuel, M.D. (2002) Climate warming and disease risks for terrestrial and marine biota. *Science*, **296**, 2158–2162.

Heller, N.E. & Zavaleta, E.S. (2009) Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, **142**, 14-32.

Hodgson, J.A., Thomas, C.D., Wintle, B.A. & Moilanen, A. (2009) Climate change, connectivity and conservation decision making: back to basics. *Journal of Applied Ecology*, **46**, 964–969

Hooper, D.U., Chapin III, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Sysmstad, A.J., Vandemeer, J. & Wardle, D.A. (2005) Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs*, **75**, 3–35.

IMPACTBIO (2016) Project Implications of climate change for Azorean Biodiversity [M2.1.2/I/005/2011].

IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.

Jenkins, C.N., van Houtan, K.S., Pimm, S.L. & Sexton, J.O. (2015) US protected lands mismatch biodiversity priorities. *Proceedings of the National Academy of Sciences*, **112**, 5081–5086.

Jones, K.R., Watson, J.E., Possingham, H.P. & Klein, C.J. (2016) Incorporating climate change into spatial conservation prioritisation: A review. *Biological Conservation*, **194**, 121-130.

Joppa, L.N., Loarie, S.R. & Pimm, S.L. (2008) On the protection of "protected areas". *Proceedings of the National Academy of Sciences*, **105**, 6673-6678.

Kier, G., Kreft, H., Lee, T.M., Jetz, W., Ibisch, P.L., Nowicki, P., Mutke, J. & Barthlott, W. (2009) A global assessment of endemism and species richness across island and mainland regions. *Proceedings of the National Academy of Sciences*, **106**, 9322-9327.

Knight, A.T., Grantham, H.S., Smith, R.J., McGregor, G.K., Possingham, H.P. & Cowling, R.M. (2011) Land managers' willingness-to-sell defines conservation opportunity for protected area expansion. *Biological Conservation*, **144**, 2623–2630

Koschke, L., Van der Meulen, S., Frank, S., Schneidergruber, A., Kruse, M., Fürst, C., Neubert, E., Ohnesorge, B., Schröder, C., Müller, F. & Bastian, O. (2014) Do you have 5 minutes to spare? – The challenges of stakeholder processes in ecosystem services studies. *Landscape online*, **37**, 1-25.

Kramer-Schadt, S., Kaiser, T.S., Frank, K. & Wiegand, T. (2011) Analyzing the effect of stepping stones on target patch colonisation in structured landscapes for Eurasian lynx. *Landscape ecology*, **26**, 501-513.

Krosby, M., Tewksbury, J., Haddad, N.M. & Hoekstra, J. (2010) Ecological Connectivity for a Changing Climate. *Conservation Biology*, **24**, 1686–1689.

Lande, R. (1993) Risk of population extinction from demographic and environmental stochasticity and random catastrophes. *The American Naturalist*, **142**, 911-27.

Larkin, J.L., Maehr, D.S., Hoctor, T.S., Orlando, M.A. & Whitney, K. (2004) Landscape linkages and conservation planning for the black bear in west-central Florida. *Animal Conservation*, **7**, 23–34.

LaRue, M.A. & Nielsen, C.K. (2008) Modelling potential dispersal corridors for cougars in midwestern North America using least-cost path methods. *Ecological Modelling*, **212**, 372-381.

Lawler, J.J., Ruesch, A.S., Olden, J.D. & McRae, B.H. (2013) Projected climate-driven faunal movement routes. *Ecology letters*, **16**, 1014–1022.

Lemoine, N., Schaefer, H. & Böhning-Gaese, K. (2007) Species richness of migratory birds is influenced by global climate change. *Global Ecology and Biogeography*, **16**, 55–64.

Loiselle, B.A., Howell, C.A., Graham, C.H., Goerck, J.M., Brooks, T., Smith, K.G. & Williams, P.H. (2003) Avoiding Pitfalls of Using Species Distribution Models in Conservation Planning. *Conservation Biology*, **17**, 1591–1600.

Lopes, P. (2008) *Assessment of climate change statistical downscaling methods: Application and comparison of two statistical methods to a single site in Lisbon*. MSc Thesis, Universidade Nova de Lisboa, Lisbon, Portugal.

Machado, A. (2009) El Género *Drouetius* Méquignon , 1942 Stat. Prom., De Las Islas Azores (Coleoptera, Curculionidae, Entiminae). *Graellsia*, **65**, 19–46.

Malcolm, J.R., Liu, C., Neilson, R.P., Hansen, L. & Hannah, L. (2006) Global Warming and Extinctions of Endemic Species from Biodiversity Hotspots. *Conservation Biology*, **20**, 538–548.

Martin, T.G., Burgman, M.A., Fidler, F., Kuhnert, P.M., Low-Choy, S., McBride, M. & Mengersen, K. (2012) Eliciting expert knowledge in conservation science. *Conservation Biology*, **26**, 29-38.

Martinez-Harms, M.J., Bryan, B.A., Balvanera, P., Law, E.A., Rhodes, J.R., Possingham, H.P. & Wilson, K.A. (2015) Making decisions for managing ecosystem services. *Biological Conservation*, **184**, 229-238.

Martins, A.M.F. (1993) The Azores - westernmost Europe: where evolution can be caught red-handed. *Boletim do Museu Municipal do Funchal*, **S2**, 181-198.

Matthews, S.N., Iverson, L.R., Prasad, A.M. & Peters, M.P. (2011) Changes in potential habitat of 147 North American breeding bird species in response to redistribution of trees and climate following predicted climate change. *Ecography*, **34**, 933–945.

Mawdsley, J.R., O'Malley, R. & Ojima, D.S. (2009) A Review of Climate-Change Adaptation Strategies for Wildlife Management and Biodiversity Conservation. *Conservation Biology*, **23**, 1080-1089.

Maxwell, S.L., Fuller, R.A., Brooks, T.M. & Watson, J.E.M. (2016) Biodiversity: The ravages of guns, nets and bulldozers. *Nature*, **536**, 143-145.

Mazaris, A.D., Papanikolaou, A.D., Barbet-Massin, M., Kallimanis, A.S., Jiguet, F., Schmeller, D.S. & Pantis, J.D. (2013) Evaluating the connectivity of a protected areas' network under the prism of global change: the efficiency of the European Natura 2000 network for four birds of prey. *Public Library of Science one*, **8**, e59640.

McGuire, J.L., Lawler, J.J., McRae, B.H., Nuñez, T.A. & Theobald, D.M. (2016) Achieving climate connectivity in a fragmented landscape. *Proceedings of the National Academy of Sciences*, **113**, 7195–7200.

McLane, A.J., Semeniuk, C., McDermid, G.J. & Marceau, D.J. (2011) The role of agent-based models in wildlife ecology and management. *Ecological Modelling*, **222**, 1544–1556.

McMichael, A.J., Woodruff, R.E. & Hales, S. (2006) Climate change and human health: present and future risks. *The Lancet*, **367**, 859-869.

McRae, B.H. & Beier, P. (2007). Circuit theory predicts gene flow in plant and animal populations. *Proceedings of the National Academy of Sciences*, **104**, 19885–19890.

McRae, B.H., Dickson, B.G., Keitt, T.H. & Shah, V.B. (2008) Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology*, **89**, 2712-1724.

Meijer, S.S., Whittaker, R.J. & Borges, P.A.V. (2011) The effects of land-use change on arthropod richness and abundance on Santa Maria Island (Azores): unmanaged plantations favour endemic beetles. *Journal of Insect Conservation*, **15**, 505–522

Miranda, P.M.A., Valente, M.A., Tomé, A.R., Trigo, R., Coelho, M.F.E.S., Aguiar, A. & Azevedo, E.B. (2006) O clima de Portugal nos séculos XX e XXI. *Alterações Climáticas em Portugal – Cenário, impactos e medidas de adaptação* (ed. by Santos, F.D. & Miranda, P.), pp. 45-113. Projecto SIAM II, Gradiva, Lisboa.

Moustakas, A. (2016). The effects of marine protected areas over time and species dispersal potential: A quantitative conservation conflict attempt. *Web Ecology*, **16**, 113–122.

Mullins, J., Ascensão, F., Simões, L., Andrade, L., Santos-Reis, M. & Fernandes, C. (2014) Evaluating connectivity between Natura 2000 sites within the montado agroforestry system: a case study using landscape genetics of the wood mouse (Apodemus sylvaticus). *Landscape Ecology*, **30**, 609–623.

Myers, N., Mittermeier, R.A., Mittermeler, C.G., Fonseca, G.A.B. & Kents, J. (2000) Biodiversity hotspots for conservation priorities. *Nature*, **403**, 853-858.

Naeem, S., Thompson, L.J., Lawler, S.P., Lawton, J.H. & Woodfin, R.M. (1994) Declining biodiversity can alter the performance of ecosystems. *Nature*, **368**, 734-737

Nardi, G. & Mico, E. (2010) *Alestrus dolosus. The IUCN Red List of Threatened Species 2010: e.T157633A5113198*. http://dx.doi.org/10.2305/IUCN.UK.2010-1.RLTS.T157633A5113198.en. 24th October 2015.

Niebuhr, B.B.S., Wosniack, M.E., Santos, M.C., Raposo, E.P., Viswanathan, G.M., da Luz, M.G.E. & Pie, M.R. (2015) Survival in patchy landscapes: the interplay between dispersal, habitat loss and fragmentation. *Scientific Reports*, **5**, 11898.

Noss, R.F. (1983) A regional landscape approach to maintain diversity. *Bioscience*, **33**, 700–706.

Nussey, D.H., Postma, E., Gienapp, P. & Visser, M.E. (2005) Selection on Heritable Phenotypic Plasticity in a Wild Bird Population. *Science*, **310**, 304-306.

Otronen, M. & Hanski, I. (1983) Movement patterns in Sphaeridium: differences between species, sexes, and feeding and breeding individuals. *Journal of Animal Ecology*, **52**, 663–680.

Parmesan, C. (2006) Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, **37**, 637–669.

Parmesan, C. & Yohe, G. (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421**, 37-42.

Pavlova, V., Grimm, V., Dietz, R., Sonne, C., Vorkamp, K., Rigét, F.F., Letcher, R.J., Gustavson, K., Desforges, J.P. & Nabe-Nielsen, J. (2015) Modeling Population-Level Consequences of Polychlorinated Biphenyl Exposure in East Greenland Polar Bears. *Archives of Environmental Contamination and Toxicology*, **70**, 143-154.

Pearson, R.G. & Dawson, T.P. (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global ecology and Biogeography*, **12**, 361–371.

Pe'er, G., Henle, K., Dislich, K. & Frank, K. (2011) Breaking Functional Connectivity into Components: A Novel Approach Using an Individual-Based Model, and First Outcomes. *Public Library of Science one*, **6**, e22355.

Pereira, M.G., Calado, T.J., Dacamara, C.C. & Calheiros, T. (2013) Effects of regional climate change on rural fires in Portugal. *Climate Research*, **57**, 187-200.

Perry, A.L., Low, P.J., Ellis, J.R. & Reynolds, J.D. (2005) Climate change and distribution shifts in marine fishes. *Science*, **308**, 1912-1915.

Peyras, M., Vespa, N.I., Bellocq, M.I. & Zurita, G.A. (2013) Quantifying edge effects: The role of habitat contrast and species specialization. *Journal of Insect Conservation*, **17**, 807–820.

Porfirio, L.L., Harris, R.M.B., Lefroy, E.C., Hugh, S., Gould, S.F., Lee, G., Bindoff, N.L. & Mackey, B. (2014) Improving the use of species distribution models in conservation planning and management under climate change. *Public Library of Science one*, **9**, e113749.

Prevedello, J.A. & Vieira, M.V. (2010) Does the type of matrix matter? A quantitative review of the evidence. *Biodiversity and Conservation*, **19**, 1205–1223.

QGIS Development Team (2016) QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org

Quartau, J.A. & Borges, P. (2003) A new species of the genus *Aphrodes* curtis from the Azores (Hemiptera, Cicadellidae). *Bocagiana*, **213**, 1-11.

R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

Railsback, S.F. & Grimm, V. (2011) *Agent-Based and Individual-Based Modeling: A Practical Introduction*. Princeton University Press, Princeton, USA.

Redpath, S.M., Young, J., Evely, A., Adams, W.M., Sutherland, W. J., Whitehouse, A., Amar, A., Lambert, R.A., Linnell, J.D.C., Watt, A. & Gutiérrez, R.J. (2013) Understanding and managing conservation conflicts. *Trends in Ecology & Evolution*, **28**, 100-109.

Rodrigues, A.S.L., Andelman, S.J., Bakarr, M.I., Boitani, L., Brooks, T.M., Cowling, R.M., Fishpool, L.D.C., da Fonseca, G.A.B., Gaston, K.J., Hoffmann, M., Long, J.S., Marquet, P.A., Pilgrim, J.D., Pressey, R.L., Schipper, J., Sechrest, W., Stuart, S.N., Underhill, L.G., Waller, R.W., Watts, M.E.J. & Yan, X. (2004) Effectiveness of the global protected area network in representing species diversity. *Nature*, **428**, 640–643.

Rodriguez-Trelles, F. & Rodriguez, M.A. (1998) Rapid micro-evolution and loss of chromosomal diversity in Drosophila in response to climate warming. *Evolutionary Ecology*, **12**, 829-838.

Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweigk, C. & Pounds, J.A. (2003) Fingerprints of global warming on wild animals and plants. *Nature*, **421**, 57-60.

Rosenzweig, C., Casassa, G., Karoly, D.J., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T.L., Seguin, B. & Tryjanowski, P. (2007) Assessment of observed changes and responses in natural and managed systems. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by Parry, M.L., Canziani, O.F., Palutikof J.P., van der Linden, P.J. & Hanson, C.E.), 79-131. Cambridge University Press, Cambridge, UK.

Roslin, T., Avomaa, T., Leonard, M., Luoto, M. & Ovaskainen, O. (2009) Some like it hot: microclimatic variation affects the abundance and movements of a critically endangered dung beetle. *Insect Conservation and Diversity*, **2**, 232–241.

Rubidge, E.M., Patton, J.L., Lim, M., Burton, A.C., Brashares, J.S. & Moritz, C. (2012) Climate-induced range contraction drives genetic erosion in an alpine mammal. *Nature Climate Change*, **2**, 285-288.

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M. & Wall, D.H. (2000) Global biodiversity scenarios for the year 2100. *Science*, **287**, 1770-1774.

Santos, F.D.S. & Miranda, P. (2006) *Alterações climáticas em Portugal: Cenários, impactos e medidas de adaptação*. Projecto SIAM II, Gradiva, Lisbon, Porrtugal.

Saura, S., Bodin, Ö. & Fortin, M.J. (2014) Stepping stones are crucial for species' long-distance dispersal and range expansion through habitat networks. *Journal of Applied Ecology*, **51**, 171-182.

Saura, S. & Torné, J. (2009) Conefor Sensinode 2.2: a software package for quantifying the importance of habitat patches for landscape connectivity. *Environmental Modelling & Software*, **24**, 135-139.

Sax, D.F., & Gaines, S.D. (2008) Species invasions and extinction: the future of native biodiversity on islands. *Proceedings of the National Academy of Sciences*, **105**, 11490-11497.

Shah, V.B. & McRae, B.H. (2008) Circuitscape: a tool for landscape ecology. *Proceedings of the 7th Python in Science Conference* (Ed. by Varoquaux, G., Vaught, T., Millman, J.), pp. 62-66, Pasadena, California, USA.

Sheridan, J.A. & Bickford, D. (2011) Shrinking body size as an ecological response to climate change. *Nature Climate Change*, **1**, 401–406.

Shoo, L.P., Hoffmann, A.A., Garnett, S., Pressey, R.L., Williams, Y.M., Taylor, M., Falconi, L., Yates, C.J., Scott, J.K., Alagador, D. & Williams, S.E. (2013) Making decisions to conserve species under climate change. *Climatic Change*, **119**, 239–246.

Silva, L., Land, E.O. & Luengo, J.L.R. (2008) *Invasive Terrestrial Flora & Fauna of Macaronesia. TOP 100 in Azores, Madeira and Canaries*. Arena, Ponta Delgada, Azores, Portugal.

Simberloff, D., Cox, J. & Mehlman, D.W. (1992) Movement Corridors: Conservation Bargains or Poor Investments? *Conservation Biology*, **6**, 493-504.

Sohl, T.L. (2014) The Relative Impacts of Climate and Land-Use Change on Conterminous United States Bird Species from 2001 to 2075. *Public Library of Science one*, **9**, e112251.

Sutherland, W.J., Pullin, A.S., Dolman, P.M. & Knight, T.M. (2004) The need for evidence-based conservation. *Trends in ecology & evolution*, **19**, 305-308.

Taylor, P.D., Fahrig, L., Henein, K., & Merriam, G. (1993) Connectivity is a vital element of landscape structure. *Oikos*, **68**, 571–573.

Theobald, D.M., Hobbs, N.T., Bearly, T., Zack, J.A., Shenk, T. & Riebsame, W.E. (2000) Incorporating biological information in local land-use decision making: designing a system for conservation planning. *Landscape ecology*, **15**, 35-45.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Peterson, A.T., Phillips, O.L. & Williams, S.E. (2004) Extinction risk from climate change. *Nature*, **427**, 145–148.

Thuiller, W., Araujo, M.B. & Lavorel, S. (2004) Do we need land-cover data to model species distributions in Europe? *Journal of Biogeography*, **31**, 353–361.

Trenberth, K.E. & Hurrell, J.W. (1994) Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics*, **9**, 303–319.

Triantis, K.A., Borges, P.A.V., Ladle, R.J., Hortal, J., Cardoso, P., Gaspar, C., Dinis, F., Mendonça, E., Silveira, L.M.A., Gabriel, R., Melo, C., Santos, A.M.C., Amorim, I.R., Ribeiro, S.P., Serrano, A.R.M., Quartau, J.A. & Whittaker, R.J. (2010) Extinction debt on oceanic islands. *Ecography*, **33,** 285–294

USGS (2016) <http://earthexplorer.usgs.gov/> November 2015.

van Etten, J. (2015) R package gdistance: distances and routes on geopgrpahical grids. https://cran.r-project.org/web/packages/gdistance/gdistance.pdf. 12th June 2016.

van Etten, J. & Hijmans, R.J. (2010) A geospatial modelling approach integrating archaeobotany and genetics to trace the origin and dispersal of domesticated plants. *Public Library of Science one*, **5**, e12060.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. & Rose, S.K. (2011) The Representative Concentration Pathways: An Overview. *Climatic Change*, **109**, 5-31.

Visser, M.E., Holleman, L.J. M. & Gienapp, P. (2006) Shifts in Caterpillar Biomass Phenology Due to Climate Change and Its Impact on the Breeding Biology of an Insectivorous Bird. *Oecologia*, **147**, 164–172.

Visser, M.E., van Noordwijk, A.J., Tinbergen, J.M. & Lessells C.M. (1998) Warmer springs lead to mistimed reproduction in great tits (*Parus major*). *Proceedings of the Royal Society B*, **265**, 1867-1870.

Vitousek, P.M., Mooney, H.A., Lubchenco, J. & Melillo, J.M. (1997) Human domination of Earth's ecosystems. *Science*, **277**, 494-499.

Vos, C.C., Berry, P., Opdam, P., Baveco, H., Nijhof, B., O'Hanley, J., Bell, C. & Kuipers, H. (2008) Adapting landscapes to climate change: examples of climate-proof ecosystem networks and priority adaption zones. *Journal of Applied Ecology*, **45**, 1722–1731.

Walther, G-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J-M., Hoegh-Guldberg, O. & Bairlein, F. (2002) Ecological responses to recent climate change. *Nature*, **416**, 389-395.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R. & Swetnam, T.W. (2006) Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science*, **313**, 490-493.

Wetzel, F.T., Beissmann, H., Penn, D.J. & Jetz, A. (2013) Vulnerability of terrestrial island vertebrates to projected sea-level rise. *Global Change Biology*, **19**, 2058–2070.

Wiens, J.A. & Milne B.T. (1989) Scaling of "landscapes" in landscape ecology, or, landscape ecology from a beetle's perspective. *Landscape Ecology*, **3**, 87-96.

Wilby, R.L., Charles, S.P., Zorita, E., Timbal, B., Whetton, P. & Mearns, L.O. (2004) *Guidelines for use of climate scenarios developed from statistical downscaling methods*. Supporting material of the Intergovernmental Panel on Climate Change (IPCC), Task Group on Data and Scenario Support for Impacts and Climate Analysis (TGICA), Rotterdam, Netherland.

Wilensky, U. (1999) *NetLogo*. <http://ccl.northwestern.edu/netlogo/> Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL.

Williams, J.C., ReVelle, C.S. & Levin, S.A. (2005) Spatial attributes and reserve design models: a review. *Environmental Modeling and Assessment*, **10**, 163–181.

Zeller, K.A., McGarigal, K. & Whiteley, A.R. (2012) Estimating landscape resistance to movement: a review. *Landscape Ecology*, **27**, 777-797

Zimov, S.A., Chuprynin, V.I., Oreshko, A.P., Chapin III, F.S., Reynolds, J.F. & Chapin, M.C. (1995) Steppe–tundra transition: a herbivore-driven biome shift at the end of the Pleistocene. *American Naturalist*, **146**, 765–794.

Chapter 6 - Supplementary materials

6.1 Materials and methods

6.1.1 Expert knowledge information

Table 6.1 - Resistance values regarding the expert knowledge, for the five species and different land-uses and threshold slope

Species	Agriculture	Uncovered areas	Exotic forest	Industrial	Lagoons	Grassland	Natural grassland	Urban	Native vegetation	Threshold slope
Alestrus dolosus	100	90	50	100	100	100	30	100	1	40
Aphrodes hamiltoni	100	50	50	100	100	100	50	100	1	40
Cedrorum azoricus azoricus	100	70	70	100	100	100	50	100	1	10
Drouetius borgesi borgesi	100	100	70	100	100	100	50	100	1	30
Trechus terrabravensis	100	100	100	100	100	100	100	100	1	10

6.1.2 Models description

6.1.2.1 ODD Protocol: Climate Change implications on landscape functional connectivity: a case study with insects in Terceira Island (Azores)

Our model description follows the ODD (Overview, Design concepts, Detail) protocol for agent-based models description, as suggested by Grimm *et al*. (2006, 2010). The model was developed in NetLogo environment (Wilensky, 1999).

OVERVIEW	**1. PURPOSE** The main purpose of this model is the creation of a connectivity map of Terceira island for the five endemic species, in order to i) evaluate the current connectivity of the Island and ii) further evaluate their vulnerability regarding climate change, and iii) ultimately propose management actions that would enhance species movement. To achieve them, the present model relies on two types of simulation: first simulation type (allowed to fulfil i and ii) and second simulation type (allowed to fulfil iii).
	2. ENTITIES, STATE VARIABLES AND SCALES The model is a spatially explicit individual-based system, where the terrestrial landscape is constrained with an ocean boundary, making it impossible to agents to jump from one edge to another. There are two types of entities in the model: insect agents (comprising five different species that are simulated one at a time) and environmental agents, i.e. patches. Insects are represented as individuals with *state variables* related to their location. Each patch is a grid cell characterized by their corresponding land-use and slope. There are other parameters related to these two variables as described below. **2.1 Parameters that characterize cell states**. For all simulations, each cell contains: **(a) landuse,** identifying nine different uses. **(b) slope** which corresponds to data of terrain slope in the island. (**c) slope.threshold**, representing the maximum value that permits movement to a specific path direction, is obtained. This parameter, although attached to each patch, depends on species modelled. Obtained through expert knowledge. **(d) resistance** to movement parameter is calculated based on land-use data. Similar to slope threshold, this parameter varies among species modelled and is also based on expert knowledge. **(e) prob.use** (probability of use) is a combination of (c) and (d) and represents the value of probability that an individual have to use a certain cell. **(f) prob.mortality** (probability of mortality) is calculated for each land-use. Derives from (d) and from a mortality parameter (see Section Sub-models). **(g) prob.use.temp** (probability of use temporary) is set to promote dispersion. A value is given to each cell, where non-stepped cells probability of use temporary remain the same as probability of

use, and stepped cells' value becomes zero.
(h) num.stepped.success (number of stepped successes) allows to record the path that each agent travelled (i.e., the cells that he stepped). Note that the duplicates are removed, meaning that each agent is only taken into account once for each cell.
(i) cluster is used to define the location of significant sized native vegetation areas.
(j) cluster.color (colour of clusters) helps visualize the areas identified in (i).
(k) edge allows to create new agents in the edge of areas identified in **(i)**.
Parameters **(i)**, **(j)** and **(k)** are exclusively important for the second simulation type.
(l) cluster.id (cluster identification) gives a unique value to each identified cluster.
(m) occurrence-sdm corresponding to the projected current species distribution (SDM stands for Species Distribution Model)
(n) future-occurrence-sdm that identifies the projected future species distribution.

2.2 Parameters that characterize agents' variable state.
(o) my-cluster identifies the cluster **(i)** where the agent is created. When second simulation type is selected, this parameter is responsible for the movement rule that is applied to the agent, and later, to end their movement (see Section sub-models).
(p) mypath (my path) tracks the cells stepped by a given agent. Particularly important for **(g)** and **(h)** parameters.
(q) move memory characterizes the typical movement of agents, taking into account **(e)** and **(g)**.
(r) prob.moving-randomly (probability of moving randomly) characterizes also agents' movement. If acting, agents ignore **(e)** and **(g)** when moving to a neighbour cell.
(s) n.steps (number of steps) dictates the maximum number of moves that each agent is capable of perform.

2.3 Scales
In both simulations types a land-use map of Terceira island is drawn. Each cell have a resolution of 100 meters and the overall landscape map have a grid of 57 330 cells. It comprises 30% of intensive grassland, 19% of agriculture, 14 % of exotic forest, 14% of native vegetation, 12% of natural grassland, 8% of urban areas, 2% of uncovered areas, 0.6% of Industrial areas, and just few cells with lagoons land-use.
Although time is not considered in the model, each tick step is used to start a new replicate within the same simulation process (until the maximum value - *n.replicates* - is reached).

3. PROCESS OVERVIEW AND SCHEDULING

The model runs over two different stages. At the beginning of the simulation a general setup is made, where all the environmental characteristics (land-use, slope, resistance, probability of use, probability of mortality, cluster) are loaded (see Table 6.2 for ABM parameters details).
We identify two types of simulations: first simulation type and second simulation type. The former seeks a model that characterizes the overall connectivity of the Island, while the latter seeks a model that identifies the corridors connecting pristine native vegetation areas. Only one simulation type per species can run at a time.

First simulation type: The simulation starts with the generation of 1000 agents randomly across the landscape at each tick. Once created, agents will move according with the probability of use (*prob.use*) that each of the surrounding cells have, unless probability of moving randomly

	(*prob.moving-randomly*) acts (see Table 6.2 for detailed movement values). After each agent had move to one of its surrounding cell, agents will have a probability of die, according with the probability of mortality (*prob.mortality*). Thereafter, each individual will once again check the surrounding cells' probability of use temporary (*prob.use.temp*), moving by weighted sample. Probability of mortality is checked each time an agent arrives to a new cell. In general, the use of high resistance cells results in a higher probability of mortality. Each agent records the all the cells where he steps, from the moment he is generated, to the cell where he dies. Ultimately the connectivity matrix for the island. When the replicate ends, and if ticks is smaller than the number of replicates (*n.replicates*) set by the modeler, a new replicate starts, and one agent is again generated in the cells in the edge of each native site. Second simulation type: Before the creation of the agents, significantly sized native vegetation patches are identified and a unique number is assessed to identify each site (*cluster.id*). Afterwards, and for every replicate in the simulation, one agent is generated at each patch in the edge of identified native areas that are within the SDM for the species considered (Current SDM or Future SDM). Agents will then update their *mycluster* value to the number that identifies the native vegetation cluster where they were born. Whenever moving in cells where *cluster.id* is different from *mycluster*, i.e. dispersing, the movement rule follows the same as in previous simulation type. However, when moving in the same *cluster.id* as *mycluster*, individuals move randomly. The mortality acts equally as in the previous simulation. However, the record of stepped cells holds a substantial difference (see Section VII). When the replicate ends, and if ticks is smaller than the number of replicates (*n.replicates*) set by the modeler, a new replicate starts, and one agent is again generated in the cells in the edge of each native site.
DESIGN CONCEPTS	**Basic principles** The model follows general knowledge the authors have on dispersion of insects and the parameters of the model derive from more than a decade of fieldwork and pitfall sampling. We consider a model for dispersion in which individuals are capable of recognizing and choosing patches that are less difficult to cross. We also assume that the best patches to stay or to cross are the most similar to the species habitat matrix (Prevedello & Vieira, 2010; Eycott *et al*., 2012). In the model, the mortality probability is dependent only on resistance value of each cell. This reflects both availability of feeding resources and predatory risk. No gender, reproduction or maximum travel distances are added due to the focus of the model being the study of connectivity and ultimately, corridors design.
	Emergence, adaptation, objective, learning, and prediction The patterns characterizing the overall connectivity of Terceira Island for the five ground-dwelling Azorean insects, as well the possible paths connecting different native areas are expected to emerge from the model. The goal is to identify those paths as possible corridors to maintain in the future as an effort to preserve the species. We predict that possible corridors can be created among different areas for species which adapt to a large set of environmental conditions. For those more restrict, i.e., with high resistance to movement, we predict that few or none corridors should emerge. Agents do not have any adaptive trait.
	Sensing

	Insects can sense the neighbours' cells probability of use value and choose where to go based on this sense (valid if movement is not random. See Section VII – Movement).
	Interaction Patches define suitable cells for insects' movement. If an agent reaches a high resistance cell, his probability of dying (prob.mortality) is greater than an agent in a low resistance cell. The identity of patches that agents use during their movement is recorded in mypath variable. When dying, patches identified in mypath add one to their num.stepped.success variable, that represents the path travelled by individuals that reached the other native site. We neglected any possible interactions (such as competition, territoriality, mating, etc.) among agents.
	Stochasticity Stochasticity is used in initializing the model, to randomly assign the locations of insects (in first simulation type). During simulations, stochasticity is also used to determine whether the movement of a given agent is random (in that particular step), and whether die at each step (related to probability of mortality).
	Collectives No collectives are simulated
	Observation In the first simulation type the number of times that a unique agent crosses a given cell is recorded in num.stepped.success state variable. This approach allows assessing the most important areas for conservation efforts and to detection of barriers (a general connectivity map of the Island is provided). Further, this same connectivity map is used to a more refined vulnerability to climate change assessment. Regarding the second simulation type, the num.stepped.success state variable is also recorded, but here it provides the information regarding the existence of corridors that can be successful used to reach another native vegetation cluster. Also the list clusters.list that contains the unique id of each native vegetation cluster, records the number of agents that reach each native site. This will produce a map of the Island that i) quantifies the overall connectivity of native vegetation sites, and ii) evaluate which are the most used corridors. Both changes in probability of use, in mortality parameter or in probability of moving randomly are expected to radically change the simulations' outputs, since they are the only parameters that characterize movement. None of the simulated movement behaviours were empirically tested by field data (e.g. radio tracking).
DETAILS	**Initialization** At initialization, the modeller chooses the species to modeller and the simulation type. Notwithstanding, in all cases the land-use, slope and resistance information are loaded as characteristics of each patch. Thereafter, probability of use and probability of mortality are calculated and added to the patches attributes. If the simulation chosen is the second simulation type, clusters of native vegetation are also identified, and the modeller has to choose the SDM timeline (Current SDM or Future SDM). Again, this spatial information is loaded as characteristics of each patch and will assist with the definition of where to create new agents. The modeller simulation choice will define the outcome.
	Input data The model uses spatial data as input to characterize patches. Such spatial data comprises land-use (DROTRH, 2008) and digital elevation model (DEM) (USGS, 2016) information. The DEM

information was further converted to slope information using QGIS Slope tool (QGIS Development Team, 2016). Also SDM information (Ferreira *et al*., 2016) for studied species and for both present and future (2080-99) climatic conditions are loaded.
Resistance data and threshold slope was obtained through expert opinion.

Sub-models

The following subsections provide full detail on how model processes are simulated.

Section I - Environment characteristics

Using NetLogo GIS extension, *patches* are displayed as grids.

Two physical variables, resistance to movement (*resistence*) and a threshold slope (*threshold.slope*), are used to classify the probability of use of a *patch* for each species simulated. For all species, native vegetation cells presented the lower fixed resistance (1). Cells comprising Industry, urban areas, Agricultural areas and Inland water were assessed with the maximum fixed resistance of 100. For semi-natural grassland, intensive grassland, uncovered areas and exotic forest the resistance values varied among simulations and among species (Table 6.1). Overall, the patches where the resistance to species movement was lower were native vegetation, semi-natural grassland and exotic forest.

Regarding the species relation with slope, the slope that corresponds to 50% of probability that agents have to use it was also obtained through expert knowledge. This was inserted in the model as *threshold.slope* state variable.

The probability of use (*P*) was then calculated for each cell, according with the following formula:

$$P = \frac{1}{1 + \left(\frac{s}{t}\right)^{k}} \times \frac{1}{r}$$

where s represents the slope; t represents the species' specific slope threshold; k is a constant value (here we used of 5) and represents the importance that slope has for each species; and r is the resistance to movement of the land-use class.

The highest probability of use was found in cells with slopes lower than the species threshold slope and native vegetation.

Finally, probability of mortality (*prob.mortality - M*) is added to cells' attributes. It is highly dependent on resistance of each cell and in a mortality parameter (*m*). It is calculated as follows (for further information see Section V – Death):

$$M = \frac{r}{m}$$

Section II - Randomly distributed (First simulation type procedure)

At the beginning of each tick, 1000 individuals are generated randomly across the Island. This procedure generates agents in all classes of land-use. Agents that fall in cells with the surrounding cells with high *resistance* and, therefore high *probability of mortality*, are more prone to cease to exist after few movements. In opposition, agents generated in cells where resistance is low (e.g. native vegetation), will persist more, using more patches, and account more to overall connectivity. This procedure ran's with replicates (*n.replicates*), i.e., the number of times that the simulation process is

started, within the same simulation. Here, each simulation ran's with 10000 replicates, originating a total of 10 million agents per species.

Section III – Movement (First simulation type procedure)

Once originated, insects will proceed to move across the Island. Agents are capable of recognize the neighbors' probability of use (*prob.use*), and move preferably to the cell with highest probability of use. This, however, do not happens at every step, due to the probability of 5% that each agent has to move randomly to one of the 4 neighbors' cell.

Because our interest is to identify patches that are more used by the species, the probability of use temporary (*prob.use.temp*) was added. This variable possesses the same value as probability of use, unless that a given agent has already used a given neighbor cell. In such case, the probability of use temporary of this cell becomes 0, ensuring that the same agent will only use an already stepped cells again if there is no other neighbor where movement is possible. This mechanism avoids the formation of loops in the movement. The agent records every cell that he steps as *mypath* variable. Later, when the agent stops his movement, duplicates are removed from this list, and it is used to change the number of stepped success (*num.stepped.success*) variable of the cells. Hence, each agent has the ability to add 1 to number of stepped success variable of each cell. This means that, even if an agent steps in the same cell multiples times, only the first is saved.

Agents will stop their movement and the simulation ends when no agents are remaining (i.e. all agents died – See Section IV) or when the maximum number of steps allowed (*n.steps* = 100) is reached. A combination of both is also possible to occur.

Section IV - Death (Both simulation type)

Mortality is introduced in the model as the cells' characteristic probability of mortality (*prob.mortality* - see Environment characteristics above for calculation formula). As cited above, it relies on the resistance value and on an arbitrary mortality parameter (*mortality-param*). The last defines the severity that land-uses represent to species (see Table 6.2). For both simulations, 3 qualitative values were introduced: High mortality (*mortality-param* = 1000), intermediate mortality (*mortality-param* = 10000) and low mortality (*mortality-param* = 50000). These values were chosen taking into consideration the lowest value that allowed dispersion and the maximum value that allowed reasonable computation time. The intermediate value was chosen to provide an intermediate mortality when compared with the extreme values.

Because agents that use high resistance cells in their path will be more prone to death, this approach ensures that agents that move predominately in suitable cells account more for the overall connectivity.

In both simulations, probability of mortality is equally applied.

Section V - Clusters identification (Second simulation type procedure)

In order to become possible the study of dispersion and connectivity between native vegetation areas, first there is the need to identify those areas. This is achieved by *clusters* command. In addition, small clusters are deleted by using the command *clean-small-clusters*. Here, a total of 22 native sites were identified.

In order to differentiate clusters, each cluster calculates its center of gravity, acquiring a unique *cluster.id* value. By adding a unique characteristic to clusters, we are able to record the amount of dispersals that each cluster receives.

	Section VI - Distributed in the edge of native vegetation + inside SDM (Second simulation type procedure) One agent is placed in the edge of each cell of the previously identified native vegetation areas (*edge* command) that is within the chosen timeline (Current SDM or Future SDM). In other words, only patches with variable *edge* set as true and *occurrence-sdm* or *future-occurrence-sdm* (depending on which timeline simulated) set as 1 (binominal language) will generate an agent. The *clusters* where an agent is created is recorded as *mycluster*. This procedure ran's with replicates (n.replicates), i.e., the number of times that the simulation process is started, within the same simulation. Here, each simulation ran's with 10000 replicates. The total number of agents generated per simulation varied among species, for it is dependent on the amount of native sites inside SDM projections. ***Section VII - Movement (Second simulation type procedure)*** Agents move freely, with no restrictions except for terrestrial boundaries. While within the native vegetation cluster where they were generated (i.e., *cluster* = *mycluster*), agents will move randomly (*random-move*), whereas while dispersing (i.e., *cluster* = 0) movement rules follow the same as in first simulation type (see Section III). Finally, when a new native vegetation cluster is reached (i.e., *cluster* ≠ *mycluster* and *cluster* ≠ 0), the agent stops and stores in the variable *mypath* (*rest-corridor* command) all the cells that he used in his movement. Later, one is added to *num.stepped.success* of each unique cell used during his dispersion. Only the path of such individuals is stored. Simulations'end follows the same criteria as in the first simulation type (see Section III), or in addition, when all agents have reached a different native vegetation cluster. Note that the more usual is the combination of these 3 criteria to end the simulation.

Table 6.2 - ABM detailed parameters regarding Chapter 2. Each parameter is presented with the value(s) used in the simulations and the formula in which was calculated (NA if not applicable). A small description is also provided in order to easily understand the importance of each parameter for the model.

Parameter	Value	Formula	Description
Slope.threshold	From 0 to 100	NA	Maximum value that allow movement, is obtained - based on expert knowledge
K	5	NA	Importance that slope has for species. Used when calculating the probability of use.
Resistance	From 1 to 100	NA	Resistance offered by each class of land-use to species movement. This set of values is unique for species. Based on expert knowledge.

Prob.use	From 0 to 1	$\frac{1}{1+\left(\frac{s}{t}\right)^{k}} \times \frac{1}{r}$	Probability that a given agent have to use a certain cell during his movement
prob.use.temp	0 or prob.use	NA	Probability of use temporary. If a given cell was already stepped by the agent it becomes 0, provided that the at least one neighbour has a probability of use higher than 0. The not-stepped cells probability of use temporary is equal to the probability of use
Prob.mortality	From 0 to 1 (used values range only from 0.0006 to 0.1)	$\frac{r}{m}$	Probability that a given agent have to die in a certain land-use. r represents resistance for each land-use and m represents the *mortality-param*
Mortality-param	50000 10000 1000	NA	Parameter of mortality.
prob.moving-randomly	0.05	NA	Probability of moving randomly
Random-move	NA	NA	Agents move randomly in the landscape
n.steps	100	NA	The maximum times that an agent is able to move. If reached, the simulation stops.
n.replicates	10000	NA	Number of replicates inside each simulation.

6.1.2.2 ODD Protocol: Implications of recent reforestations in Terceira Island (Azores) for functional connectivity – An application of a new Agent-based model

Our model description follows the ODD (Overview, Design concepts, Detail) protocol for agent-based models description, as suggested by Grimm *et al*. (2006, 2010). The model was developed in NetLogo environment (Wilensky, 1999).

OVERVIEW	**1. PURPOSE** The main purpose of this model is to evaluate the effects that reforestations can have over functional connectivity. We apply our model to a specific local in Terceira Island, where some reforestation has been conducted.
	2. ENTITIES, STATE VARIABLES AND SCALES The model is a spatially explicit agent-based system, where the terrestrial landscape is constrained, making it impossible to agents to jump from one edge to another. There are two types of entities in the model: insect agents (comprising five different species that are simulated one at a time) and environmental agents, i.e. patches. Insects are represented as individuals with *state variables* related to their location. Each patch is a grid cell characterized by their corresponding land-use and slope. There are other parameters related to these two variables as described below. **2.1 Parameters that characterize cell states** For all simulations, each cell contains: **(a) landuse,** identifying nine different uses. **(b) slope** which corresponds to data of terrain slope in the island. (**c) slope.threshold**, representing the maximum value that permits movement to a specific path direction, is obtained. This parameter, although attached to each patch, depends on species modelled. Obtained through expert knowledge. **(d) resistance** to movement parameter is calculated based on land-use data. Similar to slope threshold, this parameter varies among species modelled and is also based on expert knowledge. **(e) prob.use** (probability of use) is a combination of (c) and (d) and represents the value of probability that an individual have to use a certain cell. **(f) prob.mortality** (probability of mortality) is calculated for each land-use. Derives from (**d**) and from a mortality parameter (*m*) (see Section Sub-models). **(g) prob.use.temp** (probability of use temporary) is set to promote dispersion. A value is given to each cell, where non-stepped cells probability of use temporary remain the same as probability of use, and stepped cells' value becomes zero. **(h) num.stepped.success** (number of stepped successes) allows to record the path that each agent travelled (i.e., the cells that he stepped). Note that the duplicates are removed, meaning that each agent is only taken into account once for each cell. **(i) cluster** is used to define the location of significant sized native vegetation areas. **(j) cluster.color** (colour of clusters) helps visualize the areas identified in **(i)**. **(k) edge** allows to create new agents in the edge of areas identified in **(i)**. **(l) cluster.id** (cluster identification) gives a unique value to each identified cluster. **(m) new-site** that identifies cells where reforestation took place (either real reforestation or

conservation scenarios reforestation).

2.2 Parameters that characterize agents' variable state.

(n) my-cluster identifies the cluster **(i)** where the agent is created. This parameter defines the movement that is applied to the agent.

(o) mypath (my path) tracks the cells stepped by a given agent. Particularly important for **(g)** and **(h)** parameters.

(p) memory characterizes the typical movement of agents, taking into account **(e)** and **(g)**.

(q) prob.moving-randomly (probability of moving randomly) characterizes also agents' movement. If acting, agents ignore **(e)** and **(g)** when moving to a neighbour cell.

(r) n.steps (number of steps) dictates the maximum number of moves that each agent is capable of perform.

2.3 Scales

In the model a land-use map of all Terceira island is drawn. The modeller can then choose the area where to zoom-in from a predefined chooser, or can draw a new window in the area where the zoom is desired. The area of study simulated here is identified in the model as [86 114 107 125]. The landscape studied has 551 cells, with a resolution of 100 meters. The chosen window of study comprises 39% of native vegetation, 51% of semi-natural pastures and 10% of exotic forest plantation (values for 'Pre-reforestation' landscape). Although time is not considered in the model, each tick step is used to start a new replicate of the same simulation process.

3. PROCESS OVERVIEW AND SCHEDULING

At the beginning of the simulation a general setup is made, where all the environmental characteristics (land-use, slope, resistance, probability of use, probability of mortality, cluster) are loaded (see Table 6.3 for ABM parameters details).

Before the creation of the agents, the local of interest is zoomed-in, and the two native vegetation areas (i.e. Serra de St. Bárbara and Biscoito da Ferraria) are identified with a unique number (*cluster.id*). Afterwards, and for every tick, one agent is generated at each patch in the edge of these identified native areas, setting their *mycluster* the number that identifies the native vegetation cluster where they were born. Whenever moving in cells where *cluster.id* is different from *mycluster*, i.e. dispersing, agents will move according with the probability of use that each of the surrounding cells have, unless probability of moving randomly acts (see Table 6.3 for detailed movement values). After each agent had move to one of its surrounding cells, agents will have a probability to die, according with the probability of mortality. Thereafter, each individual will once again check the surrounding cells' probability of use temporary (*prob.use.temp*), moving by weighted sample. Probability of mortality is checked each time an agent arrives to a new cell. In general, the use of high resistance cells results in a higher probability of mortality.

When agents are moving in the same *cluster.id* as *mycluster*, agents move randomly. When the replicate ends, only agents that reached the other native site record their pathway (*mypath*). Thereafter, a new replicate starts, and one agent is again generated in the cells in the edge of each native site.

DESIGN CONCEPTS	**Basic principles** The model follows general knowledge the authors have on dispersion of insects and the parameters of the model derive from more than a decade of fieldwork and pitfall sampling. We consider a model for dispersion in which individuals are capable of recognizing and choosing patches that are less difficult to cross. We also assume that the best patches to stay or to cross are the most similar to the species habitat matrix (Prevedello & Vieira, 2010; Eycott *et al*., 2012). In the model, the mortality probability is dependent only on resistance value of each cell. This reflects both availability of feeding resources and predatory risk. No gender, reproduction or maximum travel distances are added due to the focus of the model being the study of connectivity and ultimately, corridors design.
	Emergence, adaptation, objective, learning, and prediction The improvement in functional connectivity between the two studied areas is expected to emerge from the model. The goal is to evaluate the impact of real recent reforestation can have over functional connectivity and compare it to random reforestations. For species more restrict, i.e., with high resistance to movement, we predict that fewer agents will successfully reach the other native site. Agents do not have any adaptive trait.
	Sensing Insects can sense the neighbours' cells probability of use value and choose where to go based on this sense (valid if movement is not random. See Section IV Movement).
	Interaction Patches define suitable cells for insects' movement. If an agent reaches a high *resistance* cell, his probability of dying (*prob.mortality*) is greater than an agent in a low resistance cell. The identity of patches that agents use during their movement is recorded in *mypath* variable. When dying, patches identified in *mypath* add one to their *num.stepped.success* variable, that represents the path travelled by individuals that reached the other native site. We neglected any possible interactions (such as competition, territoriality, mating, etc.) among agents.
	Stochasticity When the modeller choses the landscape scenario of 'Random reforestations', stochasticity is used before the beginning of the simulations to convert 10 *patches* (either of semi-natural pastures or exotic forest plantation) to native vegetation. During simulations, stochasticity is also used to determine whether the movement of a given agent is random (in that particular step), and whether die at each step (related to *probability of mortality*).
	Collectives No collectives are simulated
	Observation The amount of agents that reach the other native sites is recorded in *clusters.list*. This list allows comparing the effects that landscape has over the number of dispersing agents (i.e. functional connectivity). The state variable *num.stepped.success* is also recorded. This variable provides information of the corridor that can be successful used, in each landscape, to reach another native vegetation cluster. Changes in species resistance to land-use (and consequently on probability of use), in mortality

parameter or in probability of moving randomly are expected to radically change the simulations' outputs, since they are the only parameters that characterize movement.
None of the simulated movement behaviours were empirically tested by field data (e.g. radio tracking).

DETAILS

Initialization

At initialization, the modeller chooses the species to modeller, the area to model (defining as well the zoom), and the landscape to model. Three landscapes' scenarios are available: 'Pre-reforestation' landscape (without the recent reforested areas); 'Post-reforestation' landscape (which includes the recent reforested areas); and 'Random reforestation' landscape (which generates random reforestations in the landscape, in the same proportion of the ones that took place in 'Post-reforestation' landscape). The land-use, slope and resistance information are loaded as characteristics of each patch. Thereafter, probability of use and probability of mortality are calculated and added to the patches attributes, as clusters of native vegetation are identified (i.e. Serra de St. Bárbara and Biscoito da Ferraria). Naturally, the modeller choices will define the outcome.

Input data

The model uses spatial data as input to characterize patches. Such spatial data comprises land-use (DROTRH, 2008) and digital elevation model (DEM) (USGS, 2016) information. The DEM information was further converted to slope information using QGIS Slope tool (QGIS Development Team, 2016). Resistance data and threshold slope was obtained through expert opinion.

Sub-models

The following subsections provide full detail on how model processes are simulated.

Section I – Environment characteristics

Using NetLogo GIS extension, *patches* are displayed as grids. Two physical variables, resistance to movement and slope, are used to classify the probability of use of a *patch* for each species simulated. For all species, native vegetation cells presented the lower fixed resistance (1). For semi-natural grassland and exotic forest, the resistance values varied species (Table 6.1).
The slope value that each species can transpose was also obtained through expert knowledge. This was inserted in the model as *threshold.slope* state variable.
The probability of use (*prob.use* - *P*) was then calculated for each cell, according with the following formula:

$$P = \frac{1}{1 + \left(\frac{s}{t}\right)^{k}} \times \frac{1}{r}$$

where s represents the slope; t represents the species' specific slope threshold; k is a constant value (here we used of 5) and represents the importance that slope has for each species; and r is the resistance to movement of the land-use class.
The highest probability of use was found in cells with slopes lower than the species' threshold slope and with native vegetation.

Finally, probability of mortality (*prob.mortality* - *M*) is added to cells' attributes. It is highly

dependent on resistance of each cell and in a mortality parameter (*m*). It is calculated as follows (for further information see Section V – Death):

$$M = \frac{r}{m}$$

Section II - Clusters identification

In order to study of dispersion and connectivity between native vegetation areas, we need first to identify those areas. This is achieved by *clusters* command. In addition, small clusters are deleted by using the command *clean-small-clusters*. Here, only the two native sites under study were identified In order to differentiate clusters, each cluster calculates its center of gravity, acquiring a unique *cluster.id* value. By adding a unique characteristic to clusters, we are able to record the amount of dispersals that each cluster receives.

Section III – Agents generation

At the beginning of each simulation (and replicate), one agent is created in the edge of identified native clusters. Here, a total of 90 agents were generated per tick. The output data (i.e. *number.stepped.successful* and *clusters.list*) are cumulative between ticks. When *ticks* number is equal to *n.replicates* (i.e. 1500 in our simulations), the replicate ends and all the reported outputs are stored. Then, a new replicate starts with reset variables. This procedure was repeated 10 times per conservation scenario for the five species. For each scenario, a total of 1.35 million agents were generated.

Section IV – Movement

Agents move freely, with no restrictions except for window boundaries. While within the native vegetation cluster where they were generated (i.e., whenever *cluster* = *mycluster*), individuals' move randomly (*random-move*), whereas while dispersing (i.e., *cluster* = 0), agents are capable of recognize the neighbors' *probability of use temporary*, and move preferably to the cell with highest probability of use. This, however, do not happens at every step, due to the probability of 5% that each agent has to move randomly to one of the 4 neighbors' cell. Each agent records every cell that he steps in *mypath* variable. Finally, when a new native vegetation cluster is reached (i.e., *cluster* ≠ *mycluster* and *cluster* ≠ 0), the agent stops his movement and stores *mypath* list (*rest-corridor* command). The duplicated cells in *mypath* are removed, and cells referred in *myapath* list add one to *num.stepped.success* variable. Hence, each agent has the ability to add 1 to *num.stepped.success* variable of each cell. This means that, even if an agent steps in the same cell multiples times, only the first is saved. Moreover, when reaching a new native site, the native site that received the agents records it by adding 1 to *clusters.list* list. By the end of the replicate, the amount of agents that disperse from one naïve site to another can be assessed. Replicate ends when there are no agents remaining or when the maximum number of steps allowed (*n.steps* = 100) is reached.

Section V - Death

	Mortality is introduced in the model as the cells' characteristic *probability of mortality* (see Section I - Environment characteristics above for calculation formula). As cited above, it relies on the resistance value and on an arbitrary mortality parameter (*mortality-param*). The last defines the severity that land-uses represent to species (see). Here, we used an intermediate mortality level (*mortality-param* = 10000). Because agents that use high resistance cells in their path will be more prone to death, this approach ensures that agents that move predominately in suitable cells account more for the overall connectivity.

Table 6.3 - ABM detailed parameters regarding Chapter 3. Each parameter is presented with the value(s) used in the simulations and the formula in which was calculated (NA if not applicable). A small description is also provided in order to easily understand the importance of each parameter for the model.

Parameter	Value	Formula	Description
Slope.threshold	From 0 to 100	NA	Maximum value that allow movement, is obtained - based on expert knowledge
K	5	NA	Importance that slope has for species. Used when calculating the probability of use.
Resistance	From 1 to 100	NA	Resistance offered by each class of land-use to species movement. This set of values is unique for species. Based on expert knowledge.
Prob.use	From 0 to 1	$\frac{1}{1+\left(\frac{s}{t}\right)^{k}} \times \frac{1}{r}$	Probability that a given agent have to use a certain cell during his movement.
prob.use.temp	0 or prob.use	NA	Probability of use temporary. If a given cell was already stepped by the agent it becomes 0, provided that the at least one neighbour has a probability of use higher than 0. The not-stepped cells probability of use temporary is equal to the probability of use.

Prob.mortality	From 0 to 1 (used values range only from 0.0001 to 0.01)	$\frac{r}{m}$	Probability that a given agent have to die in a certain land-use
Mortality-param	10000	NA	Parameter of mortality.
prob.moving-randomly	0.05	NA	Probability of moving randomly
n.steps	100	NA	The maximum times that an agent is able to move. If reached, the agent stops.
n.replicates	1500	NA	Number of replicates that each combination ran.

6.2 Results

6.2.1 Climate Change implications on landscape functional connectivity: a case study with insects in Terceira Island (Azores)

Table 6.4 - Expert knowledge based-model and random resistances based-models' fit comparison. A total number regarding the amount of random models that outperform our model based in expert knowledge is provided. A percentage value that represents the confidence of our expert knowledge parameters (i.e. the percentage of random models that are outperformed by it) is also presented. The R^2 value obtained by the expert knowledge based-model can be compared against the mean R^2 from random based-models (that also shows the standard deviation).

Species	Number of random models with higher fit than Expert knowledge (out of 1000)	% of random models that are outperformed by Expert knowledge	R^2 value derived from Expert knowledge information	Mean R^2 derived from randomized information, with standard deviation
Alestrus dolosus	14	98.6%	0.28	0.075±0.064
Aphrodes hamiltoni	5	99.5%	0.49	0.099±0.095
Cedrorum azoricus azoricus	87	91.3%	0.23	0.092±0.093
Drouetius borgesi borgesi	13	98.7%	0.24	0.084±0.085
Trechus terrabranvensis	93	90.7%	0.21	0.083±0.085

Table 6.5 - Full quantification of the explained variability by the four modeling techniques.

Species	Modeling method	R^2 value
Alestrus dolosus	ABM	0.30
	Circuit theory	0.11
	LCP	0.004
	Dispersal Paths	0.06
Aphrodes hamiltoni	ABM	0.49
	Circuit theory	0.30
	LCP	0.01
	Dispersal Paths	0.12
Cedrorum azoricus azoricus	ABM	0.23
	Circuit theory	0.03
	LCP	0.005
	Dispersal Paths	0.04
Drouetius borgesi borgesi	ABM	0.22
	Circuit theory	0.17
	LCP	0.02
	Dispersal Paths	0.08
Trechus terrabravensis	ABM	0.23
	Circuit theory	0.03
	LCP	0.005
	Dispersal Paths	0.04

Table 6.6 - ABM's fit for the three levels of mortality per species. AIC and difference AIC (dAIC) is also provided.

Species	Mortality level	R^2 value	AIC	dAIC
Alestrus dolosus	High	0.3103975	100.6878	0
	Intermediate	0.2990113	102.2843	1.5965
	Low	0.3001528	102.1242	1.4364
Aphrodes hamiltoni	High	0.4659586	149.3513	6.9044
	Intermediate	0.4866367	143.7233	1.2764
	Low	0.4913266	142.4469	0
Cedrorum azoricus azoricus	High	0.1848612	99.81726	6.47264
	Intermediate	0.2293434	94.58852	1.2439
	Low	0.2399254	93.34462	0
Drouetius borgesi borgesi	High	0.1917264	120.7280	4.6504
	Intermediate	0.2239279	116.0776	0
	Low	0.2236385	116.1194	0.0418
Trechus terrabravensis	High	0.1710861	97.38070	6.28502
	Intermediate	0.2171967	92.18616	1.09048
	Low	0.2268765	91.09568	0

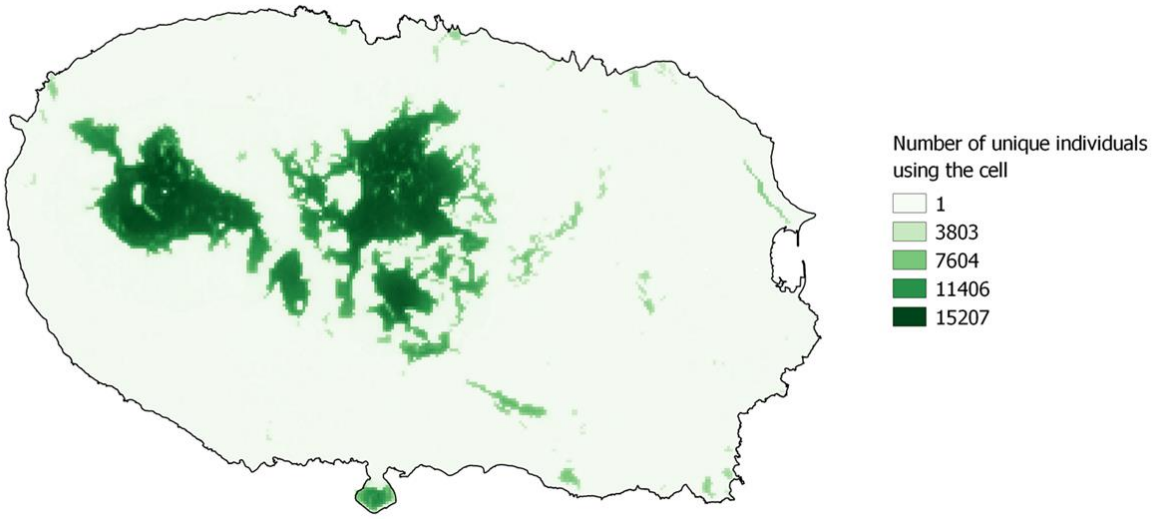

Figure 6.1 - Connectivity map generated by our ABM for *Alestrus dolosus* species. Extreme values in the scale represent the maximum and the minimum connectivity values.

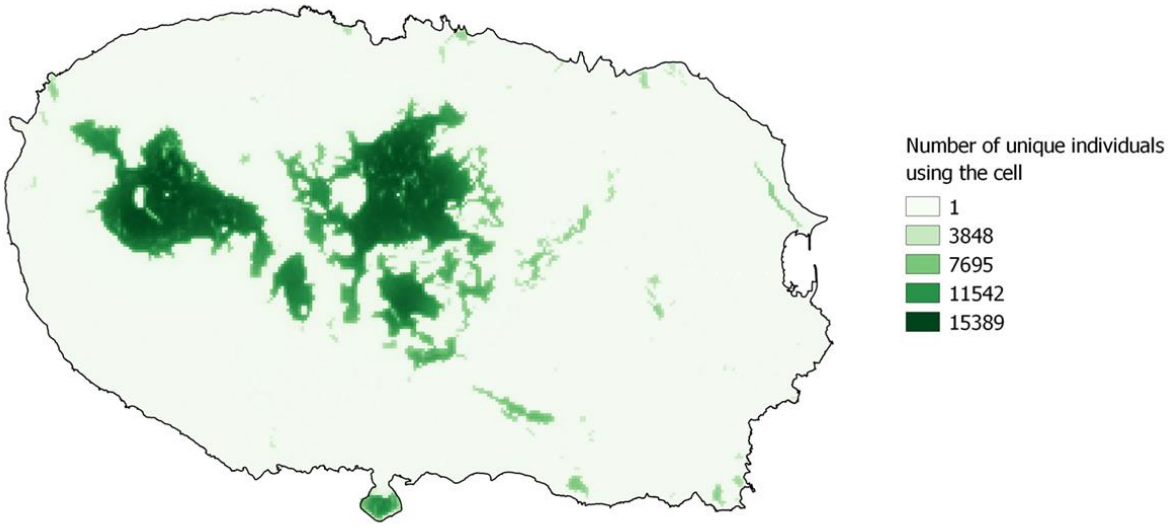

Figure 6.2 - Connectivity map generated by our ABM for *Aphrodes hamiltoni* species. Extreme values in the scale represent the maximum and the minimum connectivity values.

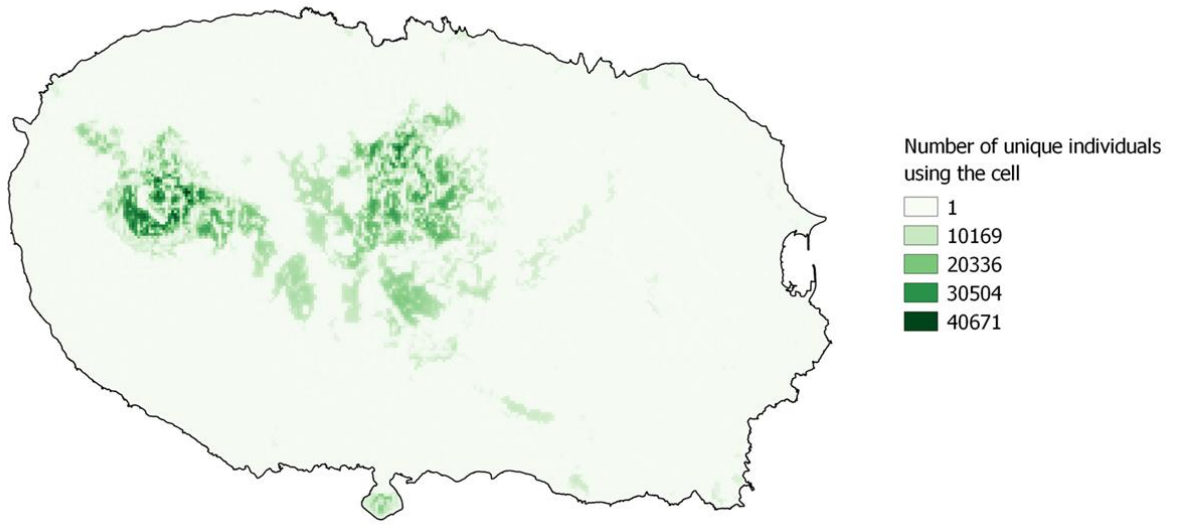

Figure 6.3 - Connectivity map generated by our ABM for *Cedrorum azoricus azoricus* subspecies. Extreme values in the scale represent the maximum and the minimum connectivity values.

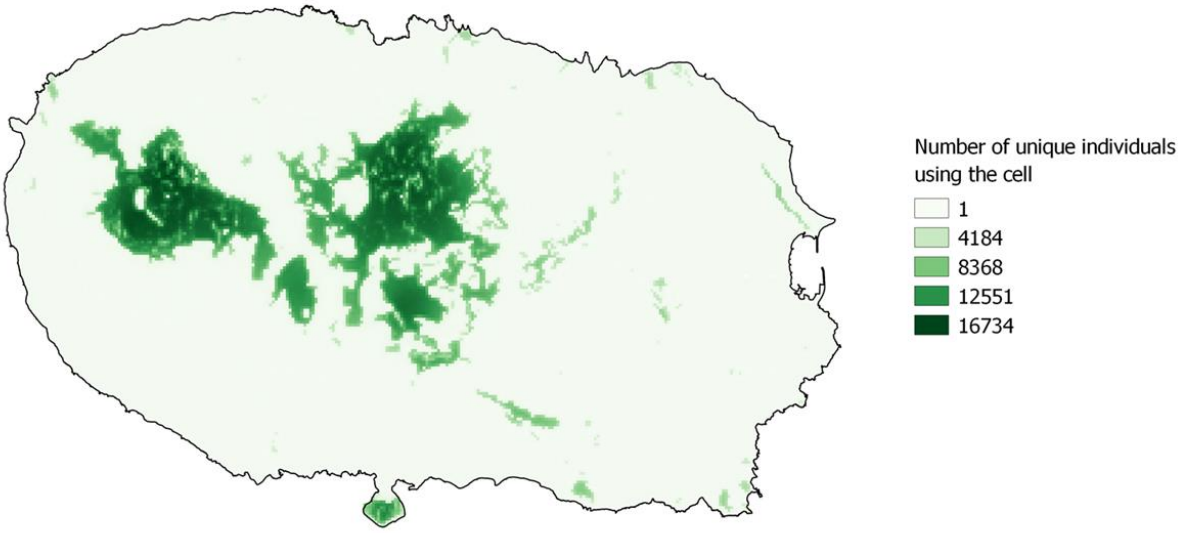

Figure 6.4 - Connectivity map generated by our ABM for *Drouetius borgesi borgesi* subspecies. Extreme values in the scale represent the maximum and the minimum connectivity values.

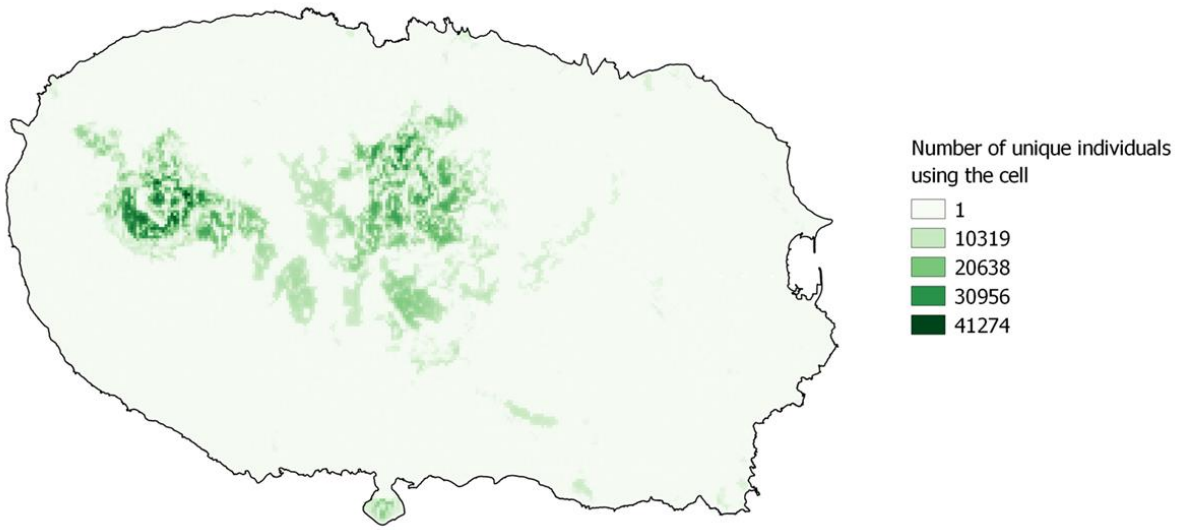

Figure 6.5 - Connectivity map generated by our ABM for *Trechus terrabravensis* species. Extreme values in the scale represent the maximum and the minimum connectivity values.

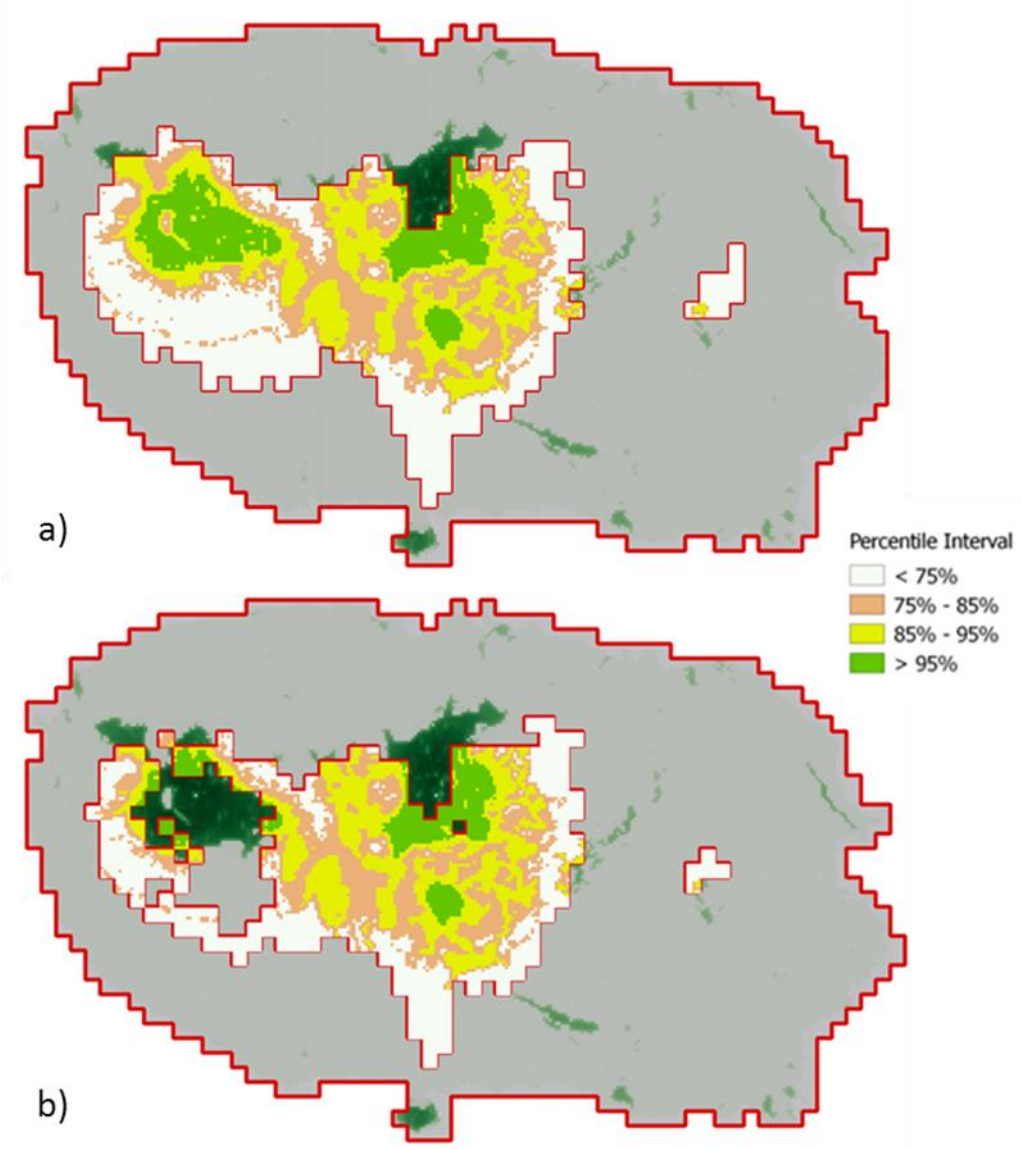

Figure 6.6 - SDM representation for *Alestrus dolosus*, for current (a) and future (b) climatic conditions. SDM areas are filled with the three levels of quality analyzed (i.e. medium, high and top quality). Suitable areas are uncovered while non-suitable ones are covered with a grid. In the background is represented the connectivity map.

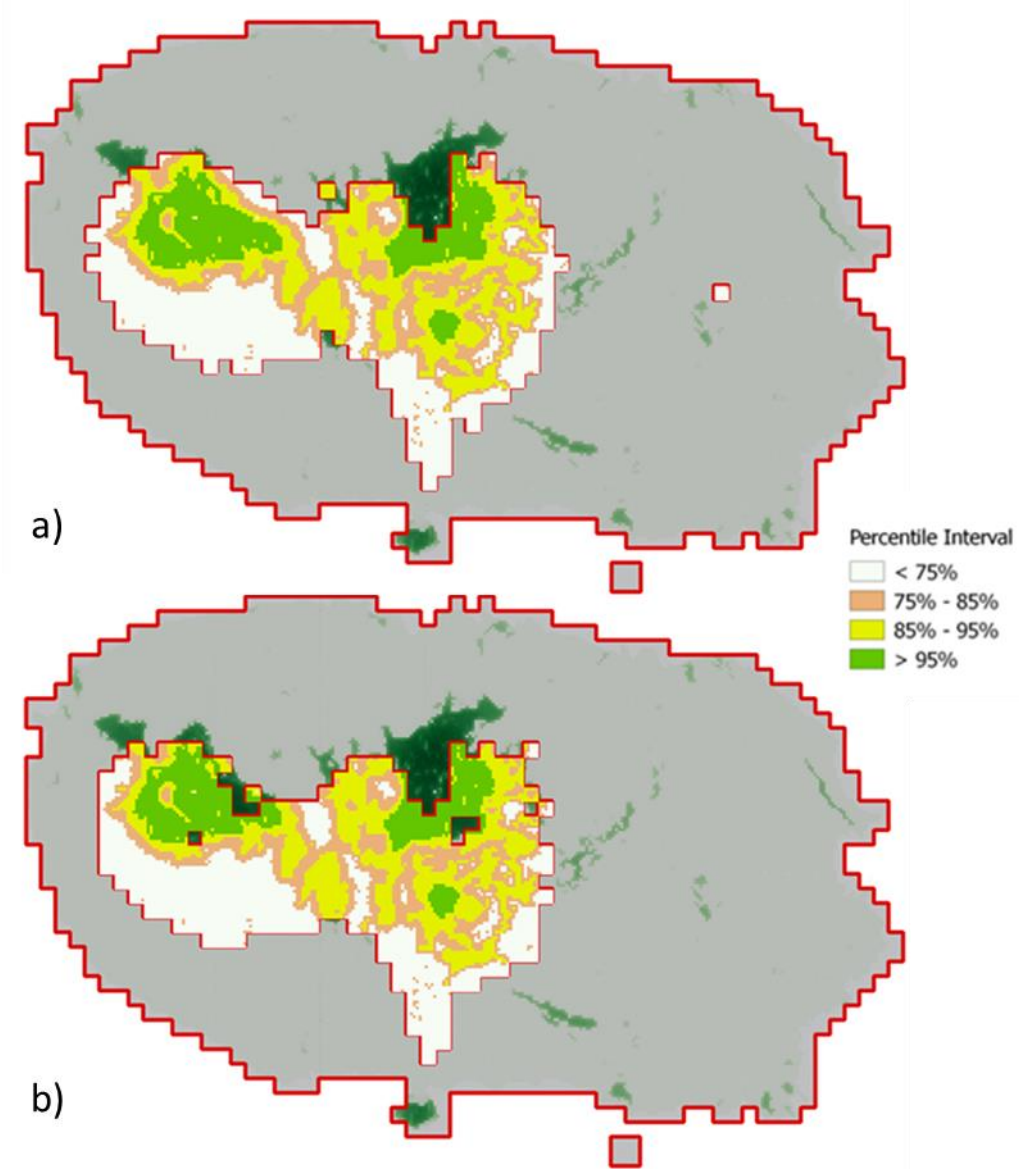

Figure 6.7 - SDM representation for *Aphrodes hamiltoni*, for current (a) and future (b) climatic conditions. SDM areas are filled with the three levels of quality analyzed (i.e. medium, high and top quality). Suitable areas are uncovered while non-suitable ones are covered with a grid. In the background is represented the connectivity map.

.

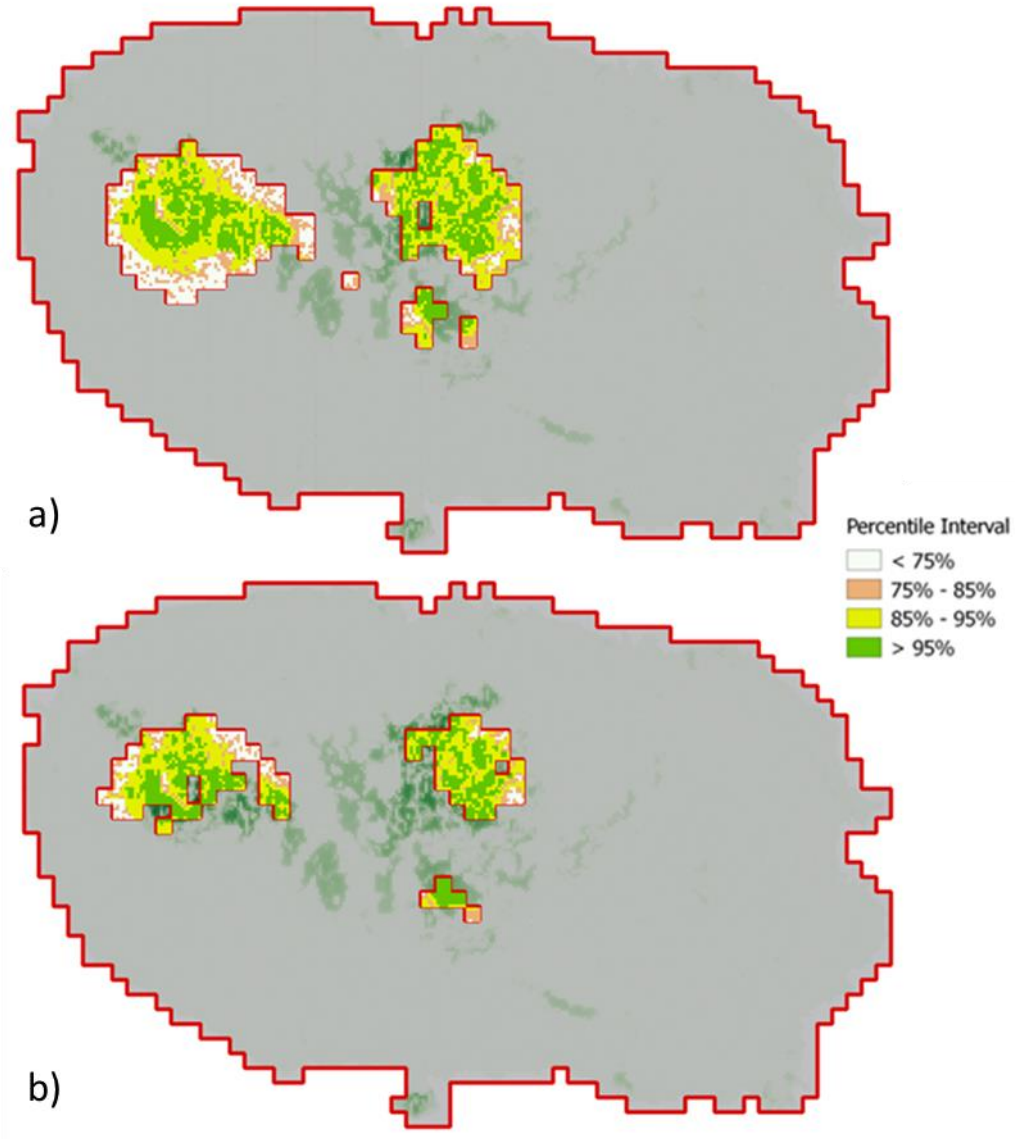

Figure 6.8 - SDM representation for *Cedrorum azoricus azoricus*, for current (a) and future (b) climatic conditions. SDM areas are filled with the three levels of quality analyzed (i.e. medium, high and top quality). Suitable areas are uncovered while non-suitable ones are covered with a grid. In the background is represented the connectivity map.

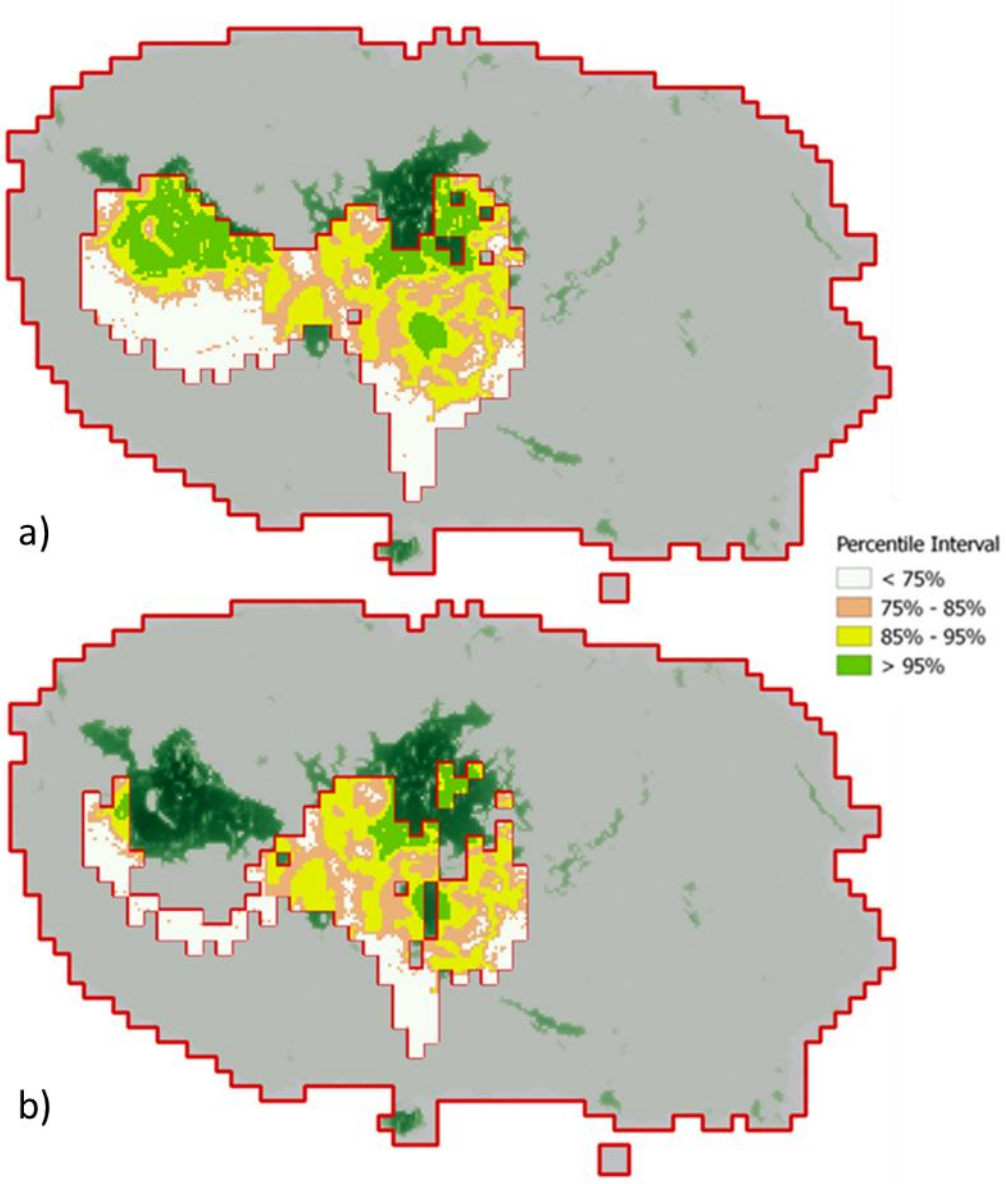

Figure 6.9 - SDM representation for *Drouetius borgesi borgesi*, for current (a) and future (b) climatic conditions. SDM areas are filled with the three levels of quality analyzed (i.e. medium, high and top quality). Suitable areas are uncovered while non-suitable ones are covered with a grid. In the background is represented the connectivity map.

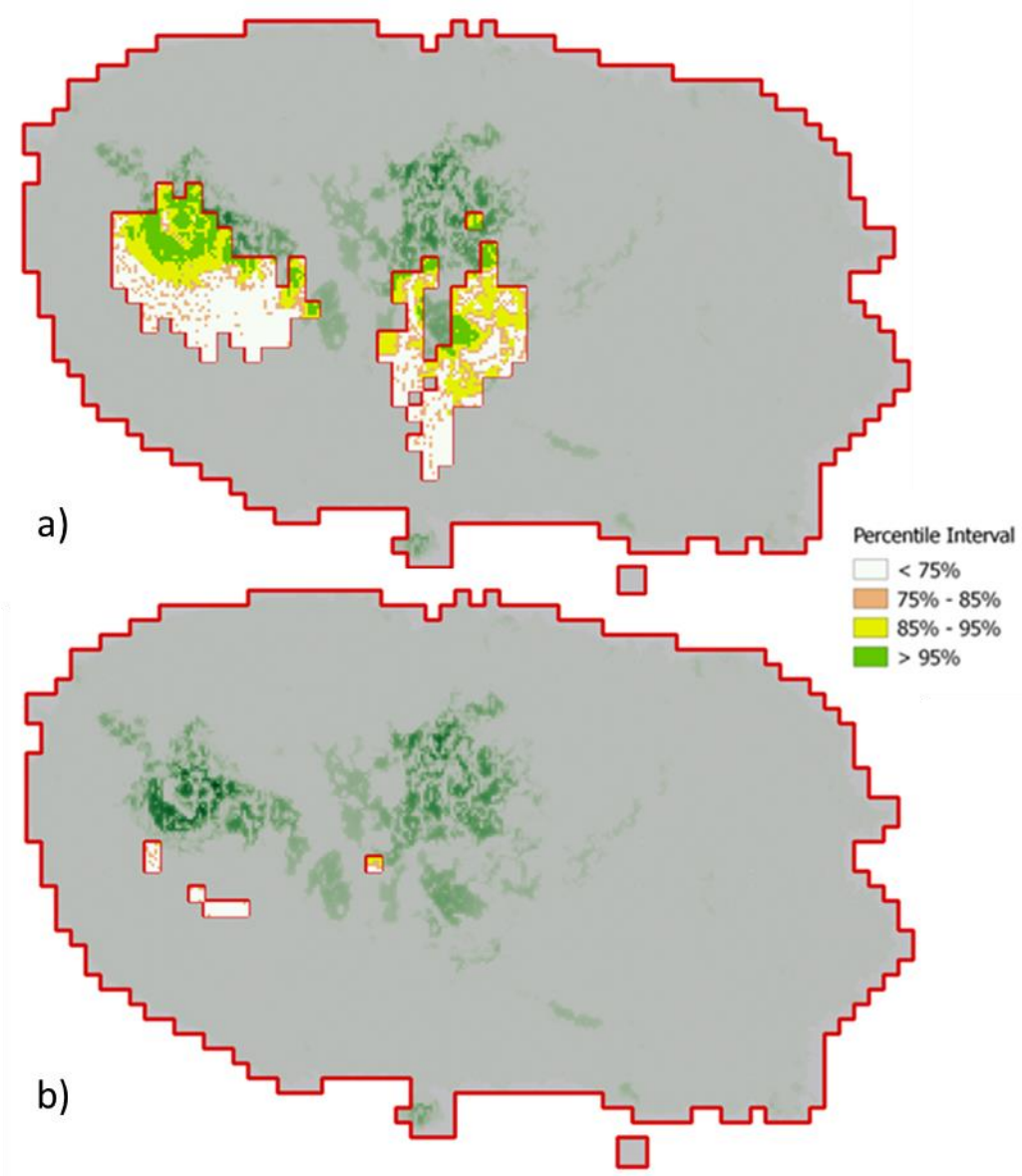

Figure 6.10 - SDM representation for *Trechus terrabravensis*, for current (a) and future (b) climatic conditions. SDM areas are filled with the three levels of quality analyzed (i.e. medium, high and top quality). Suitable areas are uncovered while non-suitable ones are covered with a grid. In the background is represented the connectivity map.

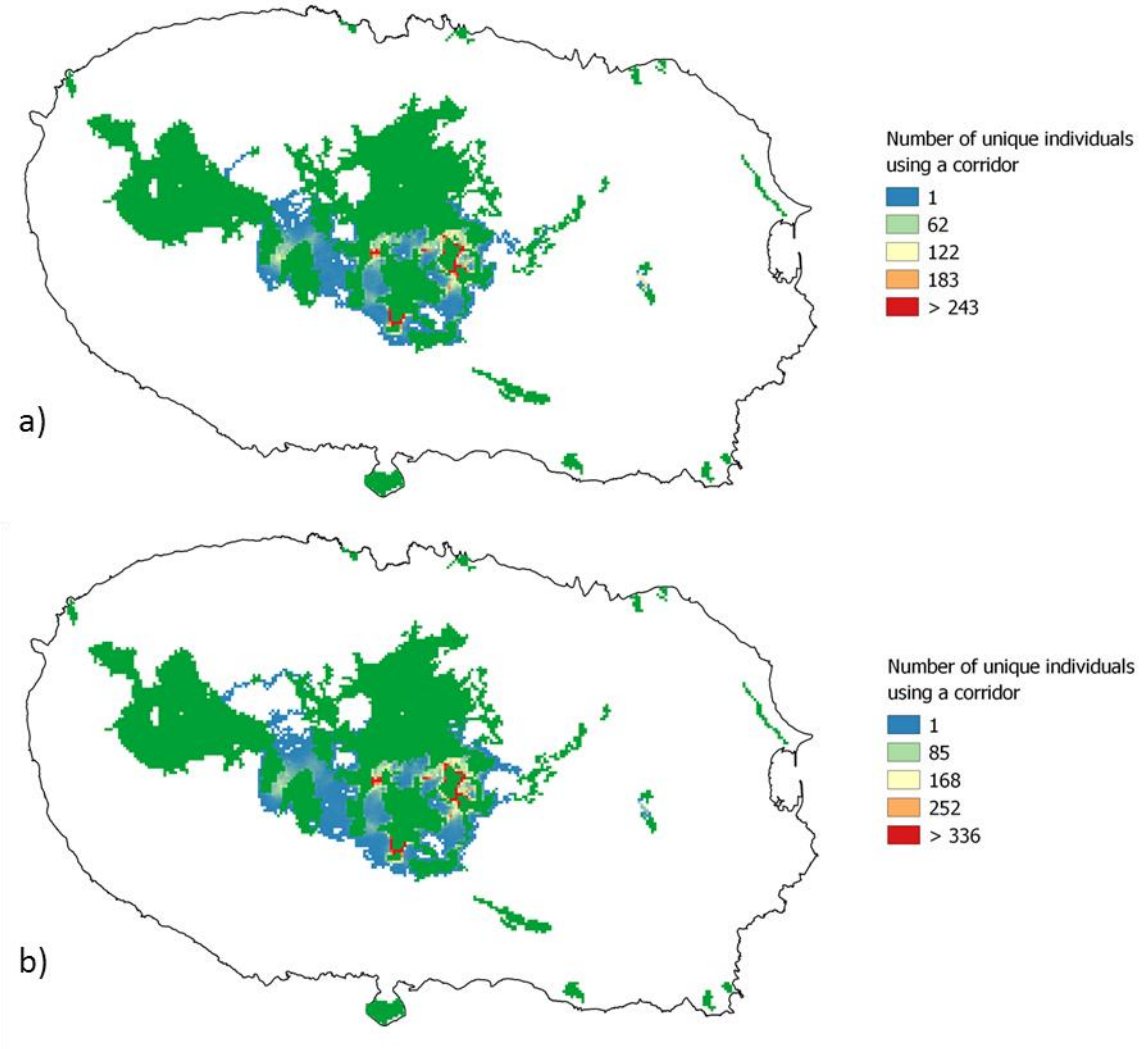

Figure 6.11 - Corridors formed by *Alestrus dolosus* dispersals, under current (a) and future (b) climatic conditions. Corridors scaled to cumulative count of 98%.

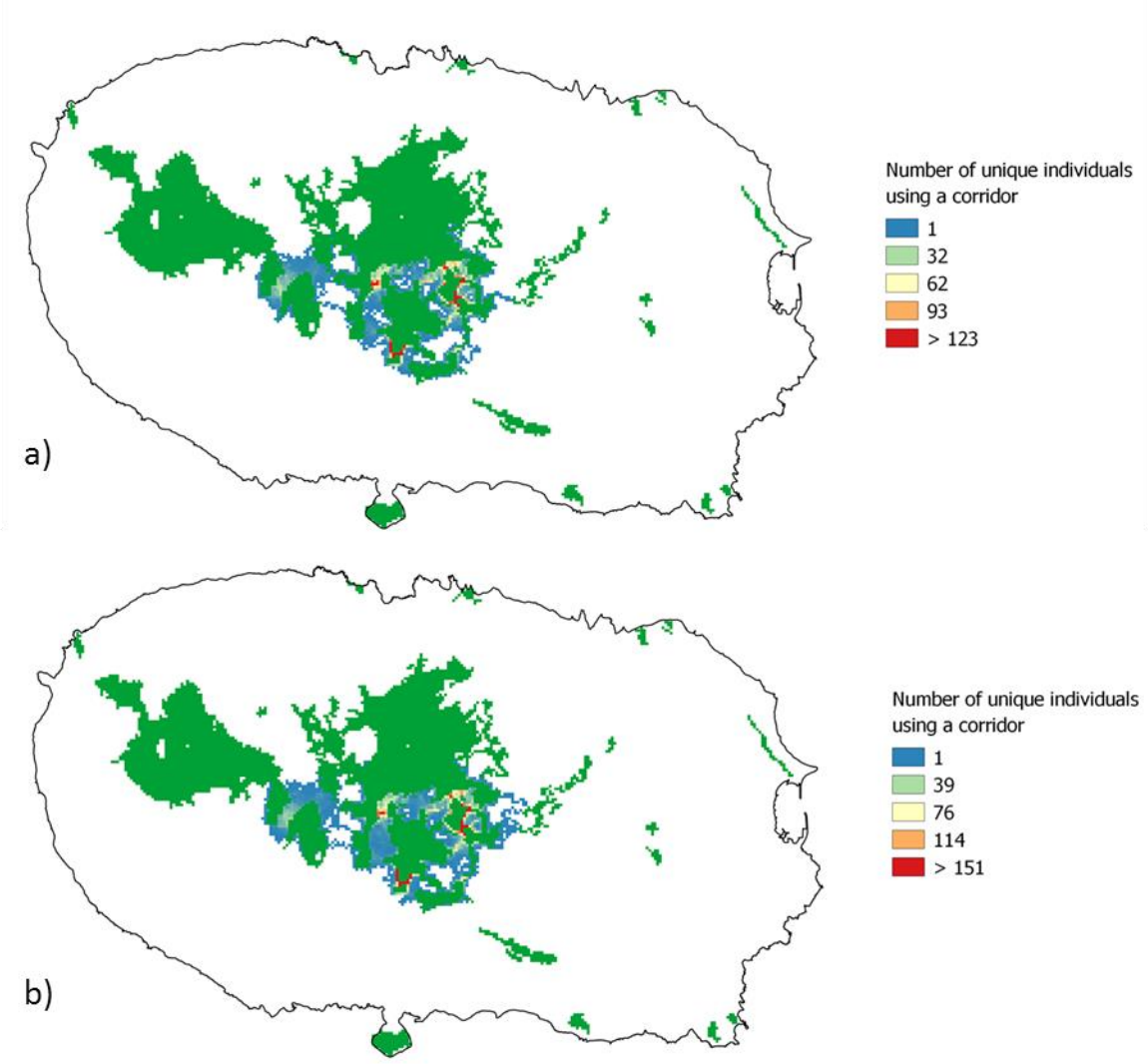

Figure 6.12 - Corridors formed by *Aphrodes hamiltoni* dispersals, under current (a) and future (b) climatic conditions. Corridors scaled to cumulative count of 98%.

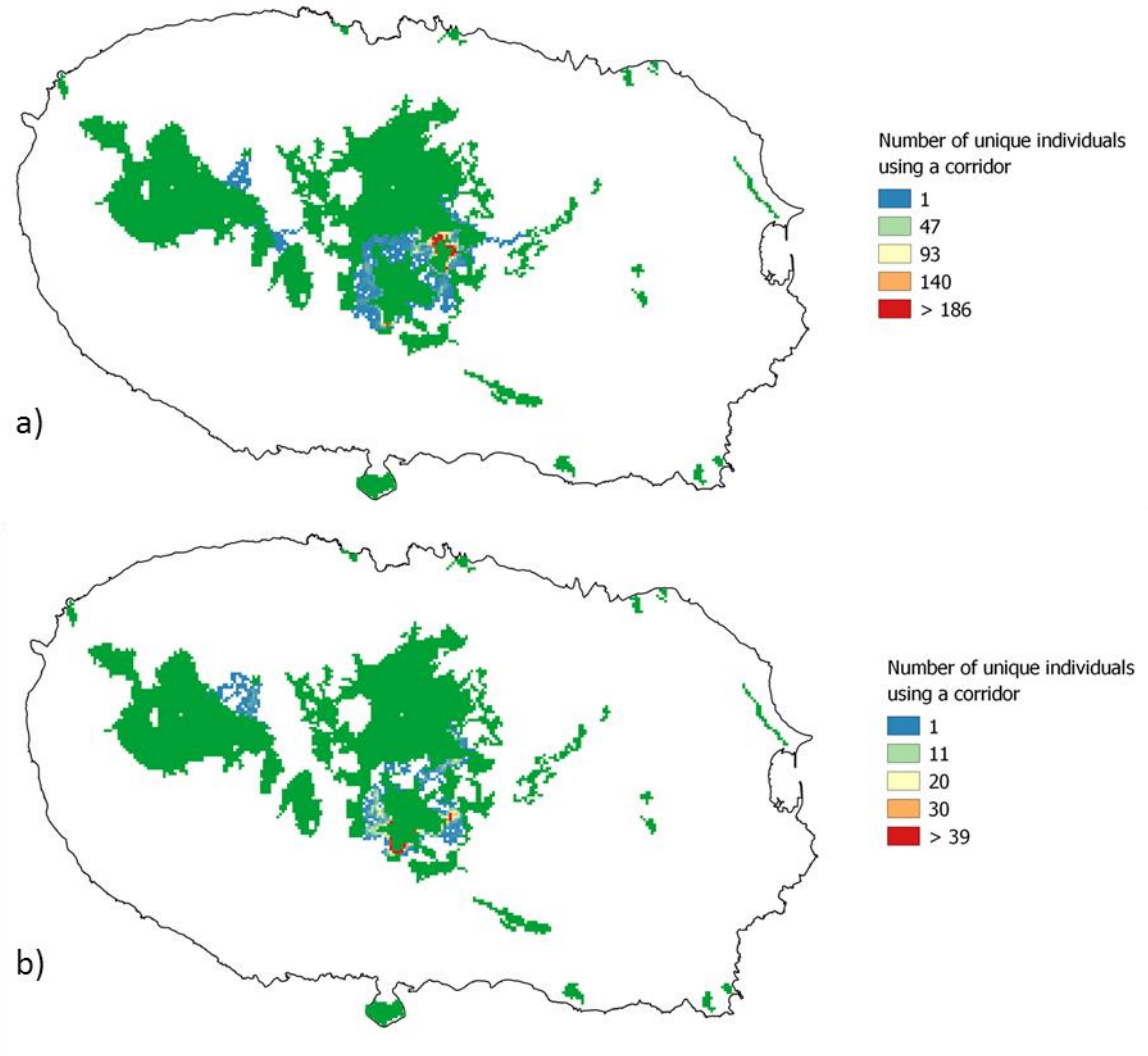

Figure 6.13 - Corridors formed by *Cedrorum azoricus azoricus* dispersals, under current (a) and future (b) climatic conditions. Corridors scaled to cumulative count of 98%.

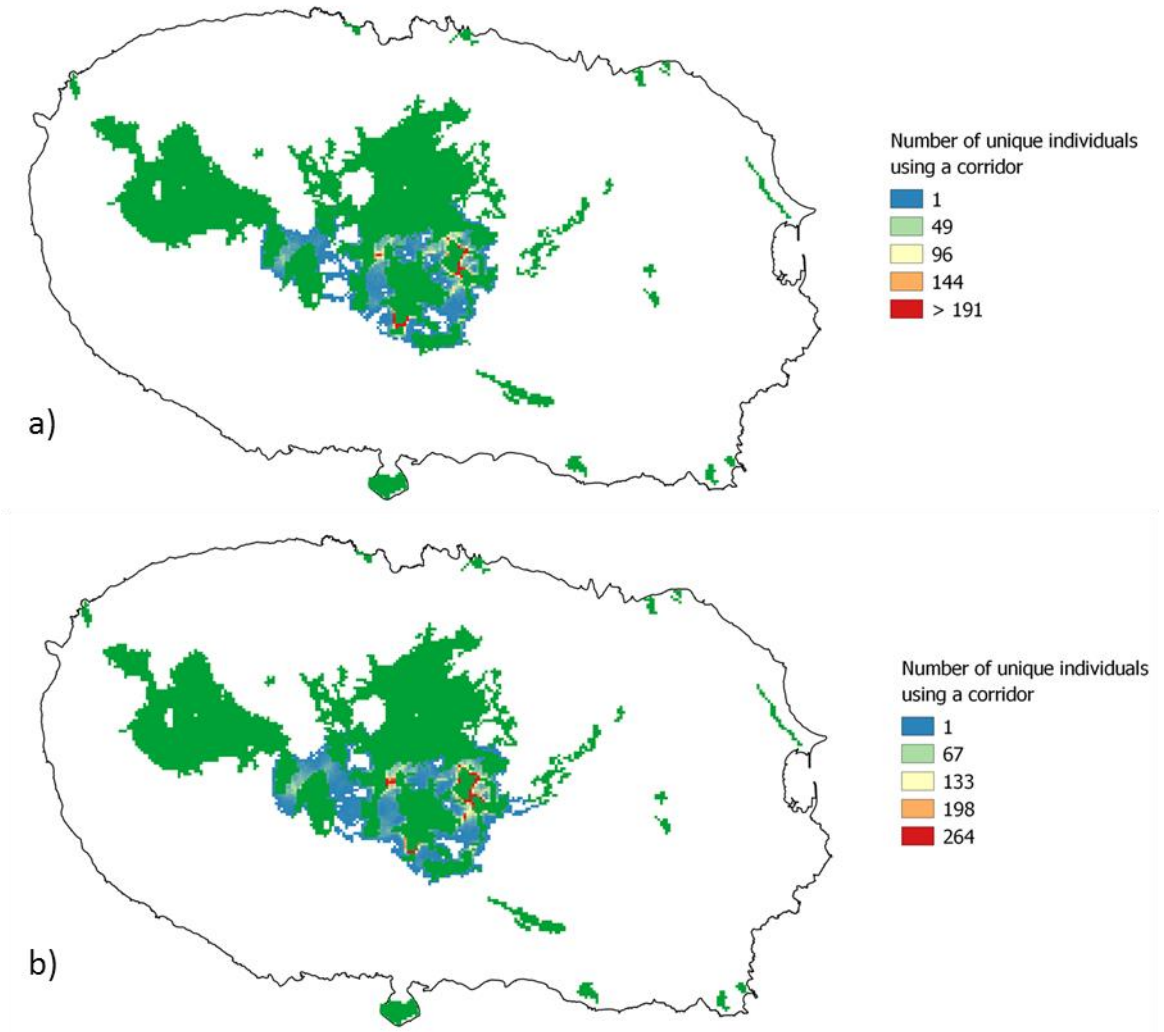

Figure 6.14 - Corridors formed by *Drouetius borgesi borgesi* dispersals, under current (a) and future (b) climatic conditions. Corridors scaled to cumulative count of 98%.

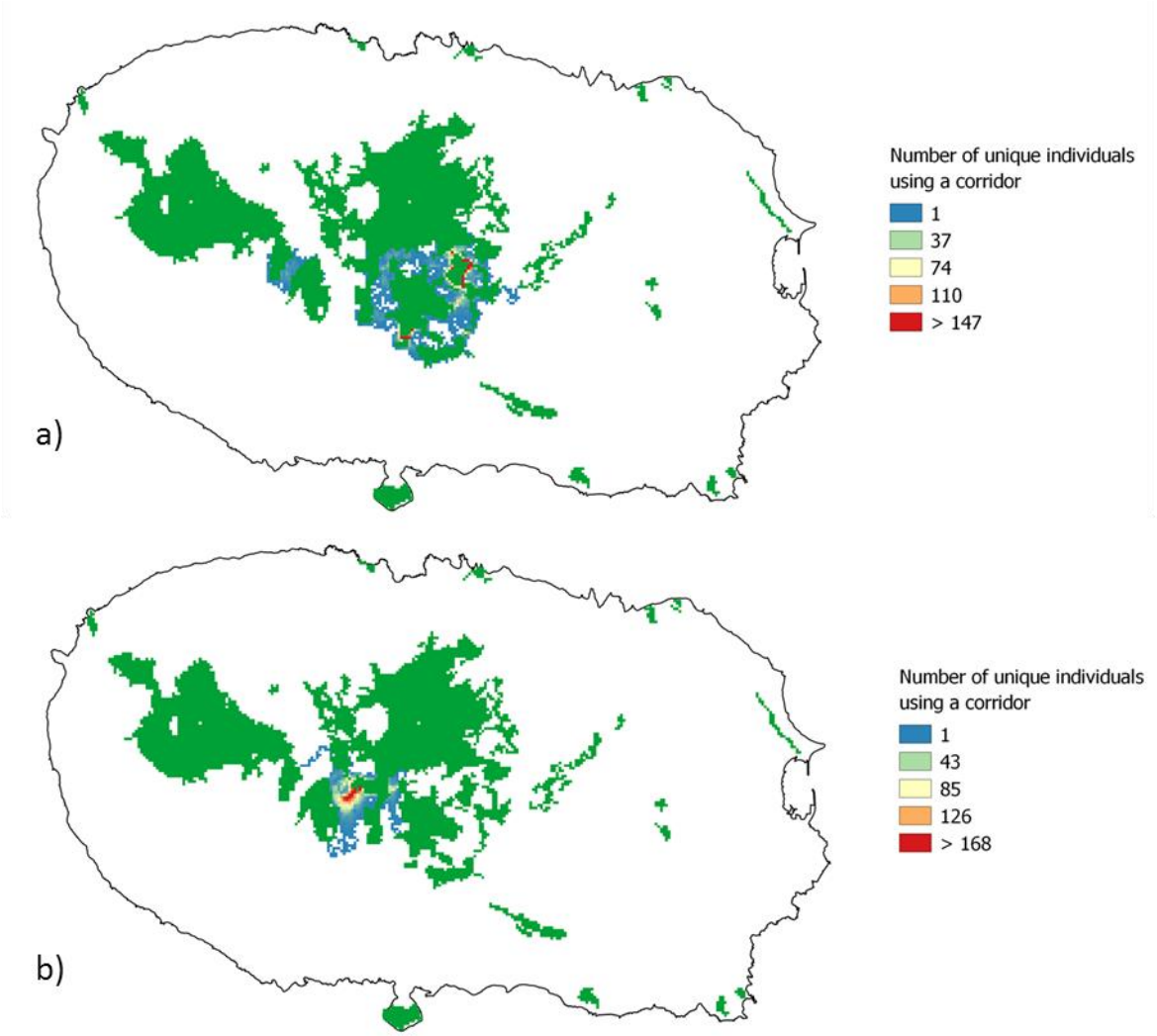

Figure 6.15 - Corridors formed by *Trechus terrabravensis* dispersals, under current (a) and future (b) climatic conditions. Corridors scaled to cumulative count of 98%.

6.2.2 Implications of recent reforestations in Terceira Island (Azores) for functional connectivity: An application of a new Agent-based model

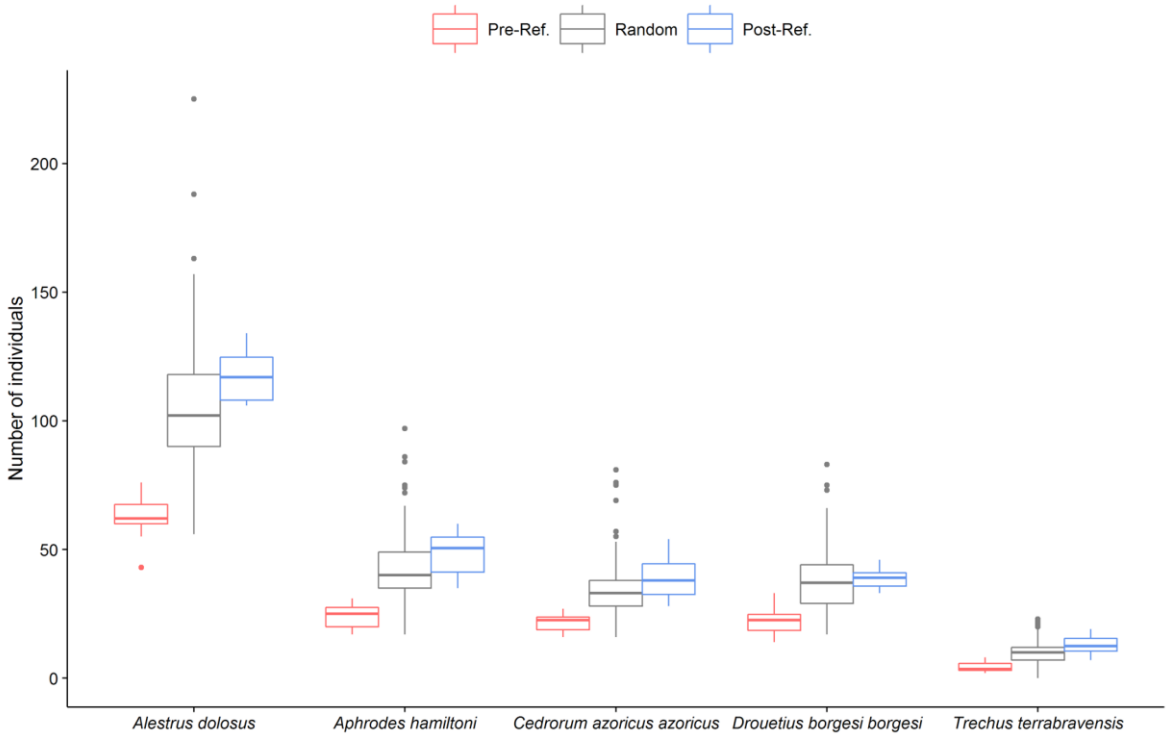

Figure 6.16 - Quantification of the pattern of functional connectivity provided by different landscapes types, per species. 'Pre-Ref.' landscape is referent to 'Pre-reforestation' landscape (in red); 'Random' landscape is referent to 'Random reforestation' landscape (with 200 different landscapes per species - in grey); 'Post-Ref.' landscape is referent to 'Post-reforestation' landscape (in blue) Dots represent outliers.

Table 6.7 - Tukey pairwise comparison test between the three scenarios of reforestation: Pre-Ref. ('Pre-reforestation'), Post-Ref. ('Post-reforestation') and Random ('Random reforestation'). Difference column is referent to the difference in the mean between the landscapes under comparison. Lower is referent to the lower value in the confidence interval while Upper is referent to the upper value for the confidence interval of the corresponding comparison. P adjusted is referent to the p-value adjusted to the 95% confidence family, for the landscapes under comparison.

Landscapes under comparison	Difference	Lower	Upper	P adjusted
Random – Pre-Ref.	19.48	7.8487	31.1123	0.0002
Post-Ref. – Pre-Ref.	24.44	8.3840	40.4941	0.0011
Post-Ref. - Random	4.96	-6.6723	16.5923	0.5766

Table 6.8 - Tukey pairwise comparison test between the ten saved 'Random reforestations' scenarios and 'Post-reforestation' landscape. Difference column is referent to the difference in the mean between the landscapes under comparison. Lower is referent to the lower value in the confidence interval while Upper is referent to the upper value for the confidence interval of the corresponding comparison. P adjusted is referent to the p-value adjusted to the 95% confidence family, for the landscapes under comparison.

Landscapes under comparison	**Difference**	**Lower**	**Upper**	**P adjusted**
Random 1 - Post-Ref.	12	-13.711825	37.711825	0.9314246
Random 2 - Post-Ref.	-3.54	-29.251825	22.171825	0.9999991
Random 3 - Post-Ref.	-3.34	-29.051825	22.371825	0.9999995
Random 4 - Post-Ref.	23.88	-1.831825	49.591825	0.0978467
Random 5 - Post-Ref.	6.34	-19.371825	32.051825	0.9996774
Random 6 - Post-Ref.	-0.76	-26.471825	24.951825	1
Random 7 - Post-Ref.	41.78	16.068175	67.491825	0.000009
Random 8 - Post-Ref.	6.78	-18.931825	32.491825	0.9993879
Random 9 - Post-Ref.	2.32	-23.391825	28.031825	1
Random 10 - Post-Ref.	-5.18	-30.891825	20.531825	0.9999561

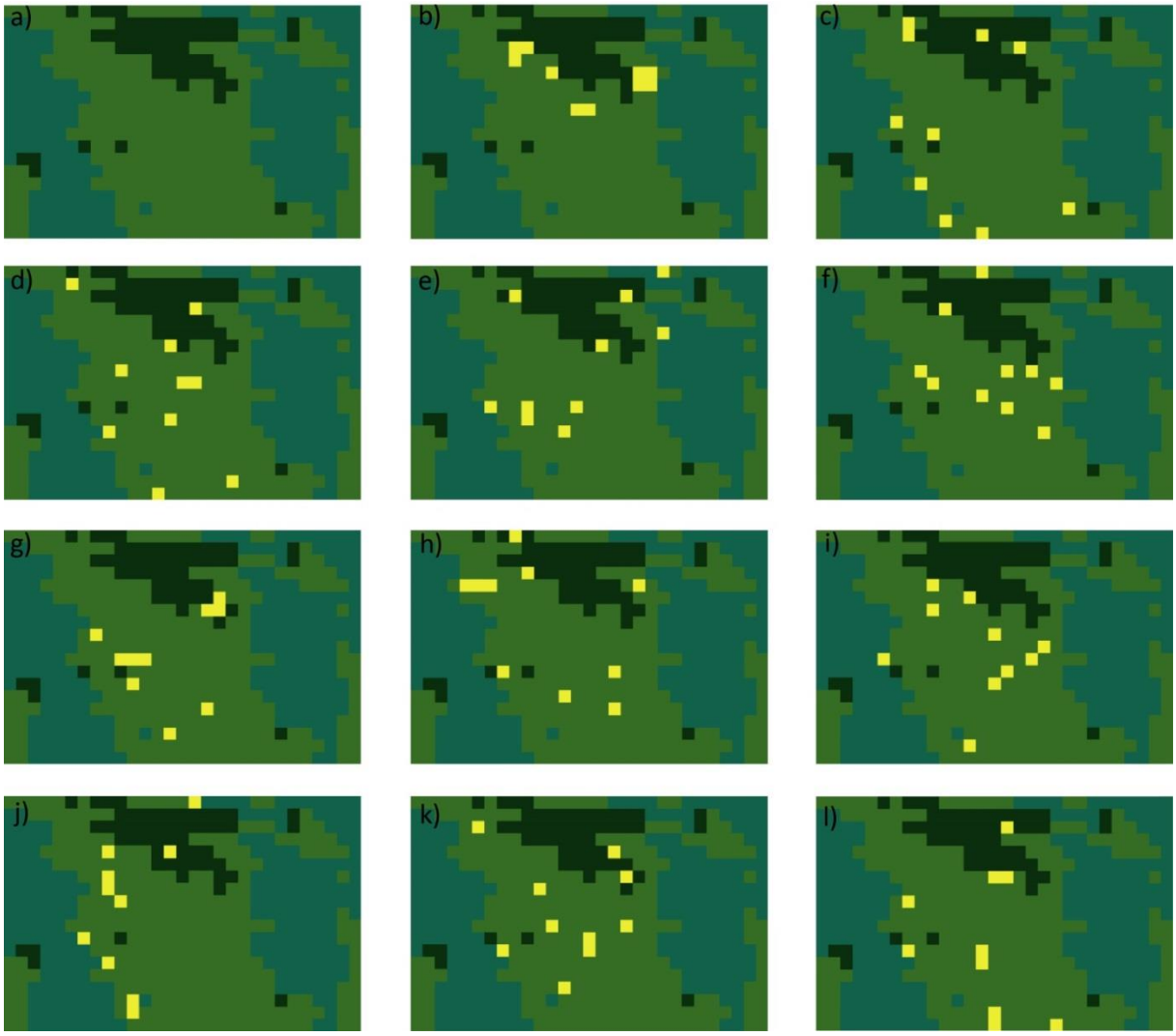

Figure 6.17 – Representation of the 12 landscapes studied in detail. Dark green-blue color indicates native vegetation areas (on the left Serra de St. Bárbara and on the right Biscoito da Ferraria). Yellow areas represent reforestations.Semi-natural grassland (green) and exotic forest plantaction (dark green) are also represented in the figure. 'Pre-reforestation' landscape (a), 'Post-reforestation' landscape (b) and 'Random reforestation' landscape (c to l) are represented. 'Random reforestation No.1' (c), 'Random reforestation No.2 (d), 'Random reforestation No.3 (e), 'Random reforestation No.4 (f), 'Random reforestation No.5 (g), 'Random reforestation No.6 (h), 'Random reforestation No.7 (i), 'Random reforestation No.8 (j), 'Random reforestation No.9 (k) and 'Random reforestation No.10 (l).